The green metamorphosis of a small open economy*

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Abstract: We develop a dynamic general equilibrium model of the green transition in a small open economy, incorporating nominal rigidities, financial frictions, and endogenous energy efficiency. Production relies on traditional inputs and energy, with limited short-run substitutability, allowing firms to gradually enhance efficiency. Carbon taxes reduce brown energy use and boost long-run efficiency but cause short-term inflation and output losses. Green public investment and subsidies can achieve similar environmental goals but require large fiscal outlays, increasing debt and sovereign spreads, and depressing consumption. In contrast, mixed strategies that recycle carbon revenues into green spending yield comparable outcomes at lower welfare costs.

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1 Introduction

Environmental disasters are an important source of macroeconomic risk, and the transition from polluting energy sources to clean energy is a central policy challenge to mitigate such risks in the long term. In this paper, we examine the costs and benefits of alternative macroeconomic policies aimed at fostering this transition in a small open economy. Although the benefits of reducing the reliance on polluting energy—often captured in the literature as lower output losses from environmental degradation—are well documented, this study contributes to the literature by focusing on the macroeconomic costs associated with fiscal and monetary policy interventions during the green transition.

We believe that policy evaluation requires a general equilibrium approach. Given our interest in fiscal and monetary policies, our model builds on the New Keynesian framework. Unlike standard models, we assume that intermediate-good production requires an energy input, in addition to traditional factors, produced with a mix of polluting and clean energy. We allow for a low substitutability between energy and traditional factors in the short run that firms can alter over longer periods through directed input-saving technical change. In addition to endogenous energy efficiency, we consider nominal frictions to study the direct impact of the green transition on inflation, as well as its indirect impact through the response of fiscal and monetary policies.

We calibrate the model to Chile, an illustrative emerging market economy that has sustained macroeconomic stability over the past three decades and has articulated clear commitments to decarbonization. Chile's Climate Action Plan 2017–2022 outlines a series of measures to promote non-conventional renewable energy, including the introduction of an energy efficiency law and a planned increase in carbon taxes. The country has set an ambitious target to reduce emissions by up to 45% relative to 2016 levels (4.6 tons of CO_2 per capita), aiming to reach 2.5 tons of CO_2 per capita by 2030. With this information, we define the green transition as a permanent reduction in the use of brown energy of approximately 45% over a 15-year horizon—broadly aligning with the government's climate objectives.

We set our base scenario as a gradual transition driven exclusively by incremental increases in an excise tax on brown energy inputs. We find that, while carbon taxes can induce this transition, they come at the cost of inflationary pressures and output losses in the short and medium term. The mechanism works as follows: anticipating higher carbon taxes, households invest in green capital, and firms gradually reduce brown energy usage. However, because green energy capacity expands only gradually, the transition le transition leads to higher prices for both brown and green energy. To adjust, firms reallocate resources to improve energy efficiency, sacrificing traditional factor productivity. This results in lower capital demand and output. The decline in output increases country spreads, further damping investment and consumption. We also show that while monetary policy can mitigate short-run inflationary costs by responding to price pressures, it cannot alleviate the associated output losses.

Next, we analyze transitions under two alternative instruments: producer subsidies for clean energy ("green subsidies") and public investment in green-energy capacity. Relying exclusively on green subsidies can reduce brown energy consumption to levels comparable to those achieved through carbon taxation over a 15-year horizon—but only if subsidies are increased by up to 400%. However, because subsidies do not put pressure on firms' marginal costs, they may result in inefficient energy use. Similarly, a substantial increase in public green investment, equivalent to 12.5% of GDP, can yield comparable reductions in brown energy consumption, though at the cost of significant fiscal pressure sustained over several years. Public investment boosts productivity in the green sector and lowers green energy prices in the long run. Likewise, subsidies reduce the relative price of green energy, albeit through a more direct channel.

In the medium term, expectations of higher future productivity stimulate firms to increase investment in traditional production factors, raising capital demand and output. This dynamic generates a transition that is both expansionary and deflationary. However, both green subsidies and public investment policies entail notable short-term consumption costs. While these measures enhance the long-term growth trajectory of the economy, they also impose significant fiscal burdens, leading to a rising debt-to-GDP ratio. In a small open economy setting, these fiscal pressures are further amplified by the interplay between real exchange rate depreciation, increasing country risk premiums, and constrained access to external financing. The resulting fiscal strain contributes to higher sovereign spreads, which in turn suppress consumption.

In terms of welfare, carbon taxes can be detrimental even if they induce a reduction in brown energy and enhance energy efficiency. Instead, we show that a mixed policy that uses carbon tax revenues to fund green subsidies or green public investment can improve welfare without significantly increasing fiscal stress. Even in countries with a longer track record of carbon pricing, proposals to raise rates still face public resistance. As shown by Ewald et al. (2022), a lack of trust in government and skepticism about the Pigouvian rationale are key factors behind this opposition. In light of the documented resistance to carbon tax increases, our results suggest that policy mixes combining moderate carbon tax hikes with modest green subsidies or public investment can achieve comparable reductions in brown energy usage at a lower welfare cost.

The existing literature on climate change policy has focused mainly on carbon taxes as a Pigouvian tool to reduce emissions (e.g., Golosov et al. (2014); Aghion et al. (2016); Hassler et al. (2021), and Angelopoulos et al. (2010), among others). Some studies, such as those of Acemoglu et al. (2012), emphasize the importance of combining carbon taxes with research and development (R&D) subsidies to maximize their effectiveness. However, limited attention has been given to other fiscal instruments, such as green public investment or subsidies, particularly in the context of small open economies. This paper fills this gap by evaluating the effects of these tools on both real and nominal macroeconomic variables along the transition.

Our study also contributes to the understanding of the transitional dynamics and macroeconomic trade-offs of climate policy in small open economies. We extend the standard E-DSGE framework by incorporating endogenous energy efficiency and nominal rigidities, allowing firms to reallocate internal resources to respond to relative energy price movements. This mechanism generates non-monotonic medium-run dynamics that are absent from existing models. Unlike previous studies, we explicitly evaluate the effectiveness of multiple fiscal instruments—carbon taxes, subsidies, and public green investment—and assess their welfare implications under financial frictions and openness. In doing so, our model captures key supply-side effects of climate policy that shape both short-term adjustment costs and long-run growth outcomes. This work contributes to the growing literature on E-DSGE models with climate features (e.g., Annicchiarico and Di Dio (2015), Annicchiarico and Di Dio (2017), Carattini et al. (2021), Economides and Xepapadeas (2019)), and complements recent studies examining monetary policy and inflation dynamics in the context of the green transition (e.g., Nakov and Thomas (2023), Olovsson and Vestin (2023), Coenen et al. (2023), Del Negro et al. (2023), Sahuc et al. (2024), Ferrari and Nispi Landi (2024)).

The rest of the paper is organized as follows: Section 2 presents the model. Section 3 discusses the calibration and solution method. Section 4 presents the transitional dynamics and offers sensitivity analysis when analyzing a transition based solely on increases in carbon taxes. Section 5 discusses alternative policy tools and different policy experiments. Section 6 quantifies welfare along the green transition. Finally, Section 7 concludes.

2 The model

We extend a small open economy New Keynesian model by incorporating energy efficiency in production, directed technological change, and green energy production. The domestic economy consists of households, final goods producers, intermediate goods firms, green energy producers, a fiscal authority, and a monetary authority setting interest rates. Energy efficiency reduces the energy intensity of intermediate goods, while directed technological change drives improvements in energy-efficient technologies.

The government environmental policy determines taxes on brown energy, subsidies to green energy production, and investment in green infrastructure to support a cleaner economy. The budget is balanced with lump-sum taxes and debt issuance.

The rest of the world demands home-produced intermediate goods, and supplies (or demands) brown energy at international prices. Additionally, the economy has access to international capital markets, where it trades a risk-free asset with a spread reflecting country-specific risk.

2.1 Households

The representative household consumes c_t and supplies labor inelastically, $\bar{h}$.[1] Households can save in a government bond, B_{t+1}, yielding a nominal return R_t after one period, and can save or borrow with a foreign bond, B^*_{t+1}, which offers a return in foreign currency of $R^*_t \Phi^A_{t+1}(\tilde{A}^f_{t+1})$, where $\Phi^A_{t+1}(\tilde{A}^f_{t+1})$ represents the spread on domestic bonds. Additionally, the household chooses green investment i^G_t, traditional investment i_t, that increase the green capital stock s^G_{t+1}, and traditional capital stock k_{t+1}, respectively. The household pays lump-sum taxes, τ_t, and receives profits, Γ_t, from the firms in the economy. Hence, the household's problem is to maximize

[1] We do not model a labor supply choice, as it offers limited additional insights for our analysis and complicates numerical solutions.

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(c_t), \tag{1}$$

where β is the household's discount factor, subject to the following constraints:

$$i_t^G + i_t + c_t + \frac{B_{t+1}}{P_t} + FX_t \frac{B_{t+1}^*}{P_t} = \frac{B_t}{P_t} R_{t-1} + FX_t \frac{B_t^*}{P_t} R_{t-1}^* \Phi_t^A(\tilde{A}_t^f) + w_t \bar{h} + \frac{R_t^k}{P_t} k_t + \frac{R_t^G}{P_t} s_t^G + \Gamma_t - \tau_t, \tag{2}$$

where P_t is the price level, w_t is the real wage, FX_t is the nominal exchange rate, and the terms R_t^k and R_t^G denote the rental returns on traditional and green capital, respectively.

The evolution of the green capital stock follows:

$$s_{t+1}^G = (1-\delta) s_t^G - \Phi_s(s_{t+1}^G, s_t^G) s_t^G + i_t^G, \tag{3}$$

and for traditional capital,

$$k_{t+1} = (1-\delta) k_t - \Phi_k(k_{t+1}, k_t) k_t + i_t, \tag{4}$$

where δ is the depreciation rate, assumed to be the same for both green and traditional capital. The functions Φ_s and Φ_k capture the adjustment costs associated with changes in green and traditional capital, respectively.[2]

The function $\Phi_t^A(\tilde{A}_t^f)$ reflects the risk premium associated with the household's foreign bond holdings (not internalized by the household):

$$\Phi_t^A(\tilde{A}_t^f) = \exp\left\{-\varphi^A \tilde{A}_t^f\right\},$$

where $-\tilde{A}_t^f$ is the real foreign debt-to-output ratio (see also Schmitt-Grohé and Uribe

[2]We also explored a specification with time-to-build investment for both capital types. The results are qualitatively similar, so we use the standard capital adjustment costs as our baseline.

(2003) and Justiniano and Preston (2010)):

$$\tilde{A}_t^f = \frac{FX_t}{P_t\bar{Y}}\tilde{B}_t^*.$$

Here, $\bar{Y}$ denotes the steady-state output level, and $\tilde{B}^*$ denotes the aggregate foreign assets.

We present the household's optimality conditions in the appendix.

2.2 Domestic final good producer

A representative firm produces the domestic final good, $y_{H,t}$, from varieties, $y_{H,i,t}$, for i $\in [0,1]$ using the following technology:

$$y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon_P-1}{\varepsilon_P}}\,di\right]^{\frac{\varepsilon_P}{\varepsilon_P-1}}.$$

Here, ε_P is the elasticity of substitution between varieties. The optimization problem of the representative firm is the following:

$$\max_{\{y_{H,i,t}\}_{i\in[0,1]}} P_{H,t}y_{H,t} - \int_0^1 P_{H,i,t}y_{H,i,t}di,$$
$$\text{subject to } y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon_P-1}{\varepsilon_P}}\,di\right]^{\frac{\varepsilon_P}{\varepsilon_P-1}}.$$

The expression below gives the optimal demand function for variety i:

$$y_{H,i,t} = y_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon_P}. \tag{5}$$

2.3 Intermediate goods producers

Each firm in the intermediate goods sector produces a differentiated variety $y_{H,i,t}$, facing a downward-sloping demand curve, as described in equation (5). The production technology for each variety uses labor $\bar{h}_{i,t}$, physical capital $k_{i,t}$, and energy $e_{i,t}$ as inputs. Following the approach of Hassler et al. (2021, 2022), we assume the production function takes the following form:

$$y_{H,i,t} = \left[\left(A_{i,t} k_{i,t}^{\alpha} \bar{h}_{i,t}^{(1-\alpha)} \right)^{\frac{\epsilon-1}{\epsilon}} + \left(A_{e,i,t} e_{i,t} \right)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}. \tag{6}$$

$A_{i,t}$ and $A_{e,i,t}$ are input-augmenting productivity factors for traditional inputs and energy, respectively, both of which are non-stationary over time. To model the evolution of these productivity factors, we assume that each firm employs a fixed stock of researchers (equal to one) who are tasked with improving these productivities. A fraction $n \in [0, 1]$ of the researchers focus on enhancing the productivity of capital and labor, while the remaining fraction $(1 - n)$ works on improving energy efficiency, as in Hassler et al. (2022).

An alternative interpretation of n is the fraction of researchers allocated to adapting foreign R&D innovations to the domestic economy. Unlike previous studies, we allow n to be endogenous and determined by firms each period. This flexibility in research allocation is supported by empirical evidence. Studies like Alam et al. (2019) document that corporate R&D investments significantly improve firms' environmental performance through two key channels in line with the natural resource-based view theory. First, R&D facilitates technological advancements that increase production efficiency without requiring additional energy input, thereby reducing energy intensity (the energy-to-output ratio). Second, these investments promote the development of clean energy technologies crucial for transitioning to more sustainable energy systems.

Building on this evidence, we model firms' endogenous decisions to invest in energy efficiency R&D. When firms allocate more researchers to energy efficiency (lower n), they can achieve both objectives documented in the empirical literature: reducing energy intensity in equilibrium and influencing the trajectory of their energy consumption. This creates an important margin of adjustment, as firms can respond to changes in relative energy prices and environmental policies by redirecting their research efforts.

We further assume that fixing the total stock of researchers dedicated to improving capital/labor productivity versus energy efficiency essentially constrains the relative growth paths of these two sectors.[3] Specifically, the proportion of researchers allocated to each sector determines the growth rates of the corresponding productivity factors, $A_{e,t}$ and A_t, as follows:

$$g_{i,t}^{A} = \frac{A_{i,t}}{A_{i,t-1}} = 1 + Bn_{i,t}^{\phi}, \tag{7}$$

$$g_{i,t}^{Ae} = \frac{A_{e,i,t}}{A_{e,i,t-1}} = 1 + B_e(1 - n_{i,t})^{\phi}. \tag{8}$$

The parameter ϕ governs the returns to scale for researchers in both sectors, and B and B_e determine the efficiency of research efforts in increasing the productivity of traditional inputs and energy efficiency, respectively.

As these growth rate equations make clear, firms face a tradeoff when allocating researchers between traditional inputs and energy efficiency. Increasing R&D efforts in one area boosts productivity growth in that sector but reduces it in the other sector. Firms choose the optimal allocation of n to balance this tradeoff. A key parameter influencing their decision is the elasticity of substitution between traditional inputs and energy, denoted by ϵ. We assume this elasticity is close to zero in the short run (i.e., nearly Leontief). Nevertheless, the firm can alter energy efficiency over the medium to long term. By choosing n, firms can reallocate resources from capital and labor to energy efficiency,

[3] A single firm cannot influence macroeconomic trends, but given that all firms behave symmetrically in equilibrium, this assumption is innocuous.

improving the energy-to-output ratio and allowing for more flexible resource use in the medium run.

Lastly, it is important to emphasize that firms incur no costs for maintaining their fixed stock of researchers, nor do they face costs when reallocating researchers between sectors, represented by n.[4]

Concerning the energy used in the intermediate production sector, we assume it is composed of both polluting (brown) energy, $e^B_{i,t}$, and clean (green) energy, $e^G_{i,t}$, combined into an aggregate energy input. The following function defines this aggregate:

$$e_{i,t} = \bar{E}\left[(1-\zeta)\left(e^G_{i,t}\right)^{\xi} + \zeta\left(e^B_{i,t}\right)^{\xi}\right]^{\frac{1}{\xi}}, \tag{9}$$

where the parameter ζ captures the weight of brown energy in production, while ξ governs how easily firms can substitute between brown and green energy sources, and $\bar{E}$ serves as a scaling parameter. Finally, brown energy consumption is taxed with an excise tax τ^e.

Firms are monopolistically competitive and set the nominal price of their product, $P_{H,i,t}$, subject to quadratic price adjustment costs. They maximize the objective function

$$\begin{aligned}\mathbb{E}_0\Bigg\{\sum_{t=0}^{\infty}\beta^t\frac{\lambda_t}{\lambda_0}\Bigg[P_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon_P} y_{H,t} - P^G_t e^G_{i,t} - \left(P^B_t + P_t\tau^e_t\right)e^B_{i,t} - W_t h_{i,t} - R^k_t k_t - \\ \frac{\iota_{PH}}{2}\left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H\right)^2 y_{H,t}P_{H,t}\Bigg]\Bigg\}.\end{aligned} \tag{10}$$

Here λ_t is the discount factor of the firm, which coincides with the Lagrange multiplier

[4]Each firm is endowed with a fixed number of researchers, and introducing a cost for maintaining this stock has no impact on the model's results, as both the number of researchers and the associated cost remain constant over time. While introducing an explicit cost for reallocating researchers could potentially slow down the transitional dynamics, it would not alter the fundamental results regarding the effects of various fiscal policies during the transition. This assumption simplifies the model without sacrificing its general insights.

from the consumer's problem, $P_{H,t}$ is the aggregate price level, P_t^G is the price of green energy, P_t^B is the price of brown energy, τ_t^e is the excise tax, W_t is the nominal wage, $R_{t,K}$ is the rental rate of capital, $\iota_{PH} \geq 0$ quantifies price adjustment costs, as in Rotemberg (1982).

In our framework, the carbon tax is modeled as an excise tax in domestic currency levied on the use of brown energy by intermediate goods producers, $P_t\tau_t^e$, with τ_t^e being the policy variable. We do not explicitly model emissions or carbon intensity. Instead, we assume a proportional relationship between brown energy use and CO_2 emissions. While this differs from actual carbon pricing—typically defined in monetary units per ton of CO_2—it allows us to isolate the macroeconomic effects of carbon taxation without adding an emissions layer to the production function.

The optimization problem of the firm i involves choosing the allocation of researchers $n_{i,t}$, price $P_{H,i,t}$, and inputs of production $e_{i,t}^B$, $e_{i,t}^G$, $k_{i,t}$, $h_{i,t}$, to maximize the present value of expected profits given by equation (10), subject to equations (5), (7)-(9), while taking as given input prices P_t^G, P_t^B, W_t, and the entire path of fiscal policy instruments, τ^e.

We solve for a symmetric equilibrium where all intermediate firms make the same decisions. Therefore, in what follows, we present the aggregated variables for all i. Using $\mu_{A,t}$ and $\mu_{A_e,t}$ for the Lagrange multipliers of the law of motions of efficiency, the optimal decision for $n_{i,t}$ is given by

$$\mu_{A,t} g_{t-1}^{\alpha} B n_t^{\phi-1} A_{t-1} = \mu_{A_e,t} B_e (1-n_t)^{\phi-1} g_{t-1}^{\mu} A_{e,t-1}, \tag{11}$$

and the optimal pricing decision results in

$$\pi_{H,t}\left(\pi_{H,t} - \bar{\pi}_H\right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1}^2 \left(\pi_{H,t+1} - \bar{\pi}_H\right) \frac{y_{H,t+1}}{y_{H,t}} \right] + \frac{\varepsilon_P}{\iota_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_P - 1}{\varepsilon_P} \right), \tag{12}$$

which is the New Keynesian Phillips curve, where $p_{H,t} = \frac{P_{H,t}}{P_t}$ is the relative price of domestically produced goods to the price level in the economy, $\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}}$ is the domestic inflation rate, and real marginal cost and the deflated domestic production are $mc_t = \frac{MC_t}{P_t}$ and $y_{H,t} = \frac{Y_{H,t}}{P_t}$, respectively. We present the rest of the optimality conditions in the Appendix.

2.4 Energy sectors

2.4.1 Green energy production

Green energy is produced domestically using private green capital s_t^G and public green capital $s_t^{G,P}$, which is chosen by the government and firms treat as given. The production function is

$$e_t^G = \Omega L^{1-\eta}[(1-\gamma)(s_t^G)^\omega + \gamma(s_t^{G,P})^\omega]^{(\eta/\omega)}, \tag{13}$$

where L is a fixed land factor (assumed to be 1), and Ω represents clean energy productivity. Parameters ω and γ determine the elasticity of substitution and the relative importance between private and public green capital. Parameter η represents the green capital share in production.

Firms solve a static optimization problem, renting private green capital s_t^G to maximize profits, given prices P_t^G, R_t^G, technology, public green capital, and a government subsidy $s_t^{P_e}$.[5] Profits in period t are expressed as follows:

$$\Gamma_t^G = (1 + s_t^{P_e})P_t^G e_t^G - R_t^G s_t^G.$$

In the benchmark calibration, we assume that public and private green capital are substitutes and investigate the sensitivity of our results to this assumption later in the analysis.

[5] We also consider the case of subsidizing purchases of green energy from the intermediate good producer, and the transitional dynamics are similar.

2.4.2 Brown energy endowment

To simplify the model, we assume there is no production of brown energy in the economy. The economy receives an endowment of brown energy, $e^{B,d}$, that we assume is traded internationally and can be exported or imported at the international price $P^{B,*}$. Since e_t^B is the domestic demand for brown energy, the imports of brown energy, $e_t^{B,*}$, are given by:

$$e_t^{B,*} = e_t^B - e^{B,d}.$$

Under the law of one price, the domestic price of imports equals the foreign price adjusted by the nominal exchange rate. We assume it holds for the brown energy market and, thus, the domestic price of brown energy is the following

$$P_t^B = FX_t P^{B,*}.$$

From the previous expression, note that

$$\frac{P_t^B}{P_t} = \frac{FX_t P^{B,*} P^*}{P_t P^*}$$

and

$$p_t^B = rer_t p^{B,*}$$

holds, where rer_t is the real exchange rate. The international price $P^{B,*}$ and price level P^* are assumed to be exogenous and invariant over time.

2.5 Imports of foreign goods

The economy imports foreign differentiated goods $y_{F,i,t}$, for which the law of one price holds. This means $P_{F,i,t} = FX_t P^*_{F,i,t}$. In addition, assuming a small open economy implies

$P^*_{F,t} = P^*$. Integrating over all varieties, we obtain $P_{F,t} = FX_t P^*$, which is the price level of imported goods. Dividing by the domestic price level, we get the real exchange rate:

$$p_{F,t} = rer_t = FX_t \frac{P^*}{P_t}.$$

2.6 Exports of domestic goods

The following expression gives the foreign demand for domestically produced goods:

$$c^*_{H,t} = \left(\frac{P^*_{H,t}}{P^*} \right)^{-\theta^*} y^*,$$

where θ^* is the elasticity of substitution of foreign and domestic goods in the foreign economy. As for the case of the foreign price level P^*, the foreign output y^* is exogenous from the point of view of the small open economy.

2.7 The production of final goods

Final consumption is a composite bundle of domestic goods, $c_{H,t}$, and foreign goods, $c_{F,t}$, defined by

$$c_t = \left[(1-\chi)^{\frac{1}{\theta}} c_{H,t}^{\frac{\theta-1}{\theta}} + \chi^{\frac{1}{\theta}} c_{F,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}}, \tag{14}$$

where parameter θ determines the elasticity of substitution between domestic and foreign goods, and χ determines the shares of foreign goods in domestic consumption. As is usually the case, we assume investment and government spending follows the same aggregation technology.

The domestic price level is accordingly defined by

$$P_t = \left[(1-\chi)P_{H,t}^{1-\theta} + \chi P_{F,t}^{1-\theta}\right]^{\frac{1}{1-\theta}}, \tag{15}$$

where $P_{H,t}$ and $P_{F,t}$ represent the prices of domestic and foreign goods, respectively.

2.8 Monetary authority

The central bank sets the domestic interest rate R_t following a Taylor rule that depends on inflation (π_t) and output (y_t) deviations from their steady-state value:

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}. \tag{16}$$

2.9 Fiscal authority

The fiscal authority's budget constraint is given by

$$\tau_t + \tau_t^e e_t^B + b_{t+1} = p_t^G e_t^G s_t^{P_e} + \frac{b_t}{\pi_t} R_{t-1} + i_t^{G,P} + g_{H,t}, \tag{17}$$

where b_{t+1} is real debt with one-period maturity purchased by domestic households, $g_{H,t}$ is wasteful government consumption, and τ_t represents lump-sum taxes to households, which follow the fiscal rule (see also Chen et al. (2022)):

$$\tau_t - \tau^* = \phi_\tau b_{t-1}.$$

Here, τ^* is the steady-state tax level, and ϕ_τ determines the fiscal regime. A sufficiently high ϕ_τ ensures fiscal sustainability by adjusting taxes as needed. $i_t^{G,P}$ represents public investment in green capital, contributing to the accumulation of public green capital $s_t^{G,P}$.[6]

[6]We assume that public green capital evolves according to a law of motion similar to equation 4, using the

2.10 Aggregation

Aggregating all domestic and foreign agents, we derive the market clearing condition for home-produced goods, the NIPA equation, and the definition of net exports. These expressions are as follows:

$$
\begin{gathered}
y_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} \right) + c_{H,t}^*, \\
gdp_t = c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} + \frac{\iota_{PH}}{2} \left(\pi_t^H - \bar{\pi}_t^H \right)^2 p_{H,t} y_{H,t} + nx_t, \\
gdp_t = p_{H,t} y_{H,t} - p_t^B e_t^{B,*}, \\
nx_t = \frac{FX_t}{P_t} P^* \frac{B_{t+1}^*}{P^*} - \frac{FX_t}{P_t} P^* \frac{B_t^*}{P^*} R_{t-1}^* \Psi^A \left(\tilde{A}_t^f \right).
\end{gathered}
$$

Then, net exports are defined by

$$
nx_t = rer_t b_{t+1}^* - rer_t \frac{b_t^*}{\pi^*} R_{t-1}^* \Psi^A \left(\tilde{A}_t^f \right).
$$

It is important at this stage to state that the output growth rate of the economy follows

$$
g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^\alpha}{X_{t-1}^{1-\alpha} X_{t-1}^\alpha} = \tilde{A}_t \tilde{k}_t^\alpha. \tag{18}
$$

Defining the stock of capital's trend as X_{t-1}, the trend of its productivity factor A_t grows at $X_{t-1}^{1-\alpha}$. In turn, $\tilde{A}_t$ and $\tilde{k}_t$ are the stationarized counterparts of A_t and k_t.

In the appendix, we derive the equilibrium conditions for this balanced growth path, similarly to Hassler et al. (2021).

same parameter values.

2.11 Numerical implementation and function forms

The main exercise is to study the transition between an initial steady state with large use of polluting energy to one with low use of polluting energy. For this purpose, we solve for the nonlinear perfect foresight transition between steady states, where we calibrate the initial steady state to match Chilean first-order national account and energy related moments.

We assume the utility function is constant relative risk aversion:

$$U = \frac{c_t^{1-\sigma}}{1-\sigma}.$$

Additionally, we assume quadratic adjustment costs for both traditional and green capital, specified as

$$\Phi\left(\frac{k_{t+1}}{k_t}\right) = \frac{\kappa}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2$$

and

$$\Phi\left(\frac{s^G_{t+1}}{s^G_t}\right) = \frac{\kappa}{2}\left(\frac{s^G_{t+1}}{s^G_t} - \bar{g}\right)^2,$$

where $\bar{g}$ is the average growth rate of the economy g_t at the steady state.

2.12 Calibration

The baseline calibration targets annual data from Chile after the 1990s, a period marked by the adoption of inflation targeting and greater macroeconomic stability. We list the parameter values and targets in Tables 1-3.

We fix some parameters following the existing literature and to standard values when uncontroversial. The intertemporal elasticity of substitution is $\sigma = 1$, and the annual capital depreciation rate is $\delta = 0.1$. Without affecting significantly our qualitative results, we assume that green capital depreciates at the same rate as traditional capital. The capital shares in intermediate goods and green energy production, α and η, are set at 0.26 and 0.33, respectively.

We normalized the steady-state values of the rest of the world inflation rate (π^*), the real exchange rate (rer), the international price of brown energy ($p^{B,*}$), and labor ($\bar{h}$) to 1, and set the adjustment cost of traditional and green capitals, κ, to 1.5.[7]

We set the price adjustment cost parameter, $\iota_{H,P}$, to 19. This value is tied to the average price contract length by comparing the log-linearized New Keynesian Phillips curve in the Rotemberg model to the Calvo model. Specifically, the slope of the Phillips curve relative to real marginal costs is $\frac{\varepsilon_P}{\iota_{H,P}}$ in the Rotemberg model and $[(1-\Psi)(1-\Psi\beta)/\Psi]$ in the Calvo model, where $1/(1-\Psi)$ represents the average contract length. The chosen $\iota_{H,P}$ corresponds to an average price contract duration of approximately one year.

We set the Taylor rule coefficient for the interest rate response to inflation deviations, ϕ_π, and the coefficient for interest rate persistence to 1.25 and $\rho_R = 0.75$, respectively, consistent with the quarterly estimates of Martínez et al. (2020), who conducted a Bayesian estimation of a New Keynesian model for Chile. The reaction to output deviations is $\phi_y = 0.25$, a standard value in the literature.

For the fiscal rule, we fix the coefficient ϕ_τ to 0.15, consistent with studies on fiscal and monetary policy interactions, such as Bianchi and Melosi (2017), Chen et al. (2022), and Bianchi (2021). The steady-state values of real debt $\bar{b}$ and taxes τ^* targets the average public debt-to-GDP ratio of 20% and average primary deficit of 5% in the Chilean data. We standardize one unit of brown energy usage as producing $5{,}000$ kWh of electricity, which corresponds to 1 ton of CO_2 emissions, based on estimates from the U.S. Environmental Protection Agency (EPA). Accordingly, we calibrate the carbon tax in our model so that the implied specific levy in the initial steady state equals 5 pesos per ton of CO_2, in line

[7] Given that we solve our model using perfect foresight, we cannot use the volatility of investment to output ratio to pin down the value of this parameter. Additional exercises (available on request) show that higher adjustment costs slow green capital accumulation, raising green energy prices and medium-run inflation.

with Chile's baseline carbon tax level (denominated in U.S. dollars per ton of emissions, but expressed here in pesos for simplicity).

Table 1: Calibrated parameter values I

	Parameter	Target/source	Value
σ	CES elasticity in utility	Standard	1
δ	Depreciation capital	Standard	0.10
α	Capital share in production	Standard	0.26
η	Green capital share in e^G	Standard	0.33
κ	Capital Adjustment costs	Investment transition	1.5
ι_{HP}	Adj. cost of prices	Av. price duration of 1 year	19
ρ_R	Interest rate smoothing parameter	Martínez et al. (2020)	0.75
ϕ_π	Interest rate response to inflation	Martínez et al. (2020)	1.25
ϕ_y	Interest rate response to output	Martínez et al. (2020)	0.25
ϕ_τ	Tax response to debt	Standard	0.15
$\bar{b}$	Public debt-to-GDP initial steady state	Average debt-to-GDP Chile	0.21
τ^*	Lump-sum taxes at initial SS	Net deficit-to-GDP Chile 5%	0.18
τ^e	Excise tax at initial SS	Excise tax Chile	0.05
θ=θ^*	Subst. H & F in consumption	Justiniano and Preston (2010)	0.85
χ	Share F goods in consumption	Justiniano and Preston (2010)	0.24
ε_P	Elasticity subst. between varieties	Avg. markup 11%	10
β	Discount factor	Avg. inflation Chile	0.987
R^*	Gross risk free rate	3 months Tbill U.S.	1.03
φ^A	Sovereign spread parameter	Country spread Chile	0.009
ξ	Elasticity subst. energy inputs	Papageorgiou et al. (2017)	0.67
$e^{B,d}$	e^B Domestic endowment	Imported/total energy	0.5
Be	Productive efficiency researchers	Avg. growth 2.5%	0.18
ϕ	Returns to scale researchers	Hassler et al. (2021)	0.92
γ	Green public and private K	An et al. (2019)	0.44
ω	Public inv. share in e^G	An et al. (2019)	0.66
ζ	Share brown energy	Data Chile	0.3

Accordingly, the increase in the carbon tax is represented in real terms, rising from 5 to 60 of final consumption units — approximately a twelvefold increase in effective carbon pricing—to reflect Chile's stated policy trajectory. In the baseline calibration, both subsidies and public green investment are set to zero.

Following Justiniano and Preston (2010), we set the elasticity of substitution between domestic and foreign goods, in the domestic and foreign countries, θ and θ^*, equal to 0.85 and the share of foreign goods in consumption, χ, to 0.24. The elasticity between domestic varieties, ε_P, is set so that the steady-state markup is 11%. We calibrate the discount factor, β, to 0.987 to get the average inflation rate of 4%, given the average nominal risk-free rate of 3%. The parameter that characterizes the sovereign spread, ϕ_A, takes the value 0.009 to generate a consistent sovereign spread for Chile that equals 1.0082.

Regarding parameters related to the energy sector, we set the substitution of energy inputs in energy production to 0.67, following the low estimates of Papageorgiou et al. (2017) and the higher estimates of Benmir et al. (2025), assuming that the two energy inputs are substitutes. The domestic endowment of brown energy, $e^{B,d}$, is set to 0.5 to match the imported to total energy ratio in Chile, which is a 50%.[8] The coefficient Be in the evolution of energy efficiency, Ae, is calibrated to reproduce the average real per capita GDP growth rate of 1.025, according to the data, and ϕ is set to 0.92 as in estimation results from Hassler et al. (2021). Parameters in the CES aggregator of public and private green capital, γ and ω, take the values of 0.44 and 0.66, respectively, as in An et al. (2019). Thus, we assume that public and private capital are substitutes in production. An et al. (2019) estimate a nested-CES production function, whereas the two types of capital are considered separately along with labor as inputs. Due to a lack of data availability, we assume that the substitution between public and private capital in production also holds for green energy production.

To finalize the parametrization of the model, we set the share of brown energy, ζ, to 0.3 and jointly calibrate the elasticity of substitution between physical capital and energy, ϵ, the energy coefficient in the CES production, $\bar{E}$, the productivity level in green energy production, Ω, and the coefficient B in the traditional factors total factor productivity

[8] In additional exercises (available upon request), we compare the benchmark calibration with a counterfactual where the small open economy is a net importer of brown energy. The results are qualitatively similar, with slightly lower output and inflationary costs when the country is a net exporter.

(TFP), to match first order moments for Chile in the initial steady state. Our targets are the ratio of brown to total energy (e^B/e), the ratios of total investment ($i^G + i^{G,P}$), and green capital investment to GDP, and we ensure that the sum of energy ratios equals one ($e^B/e + e^G/e = 1$). The data values for these objects are presented in Table 2.

Table 2: Data moments

e^B/e	$(i + i^G + i^{G,P})/y$	$(i^G + i^{G,P})/y$	$(e^B/e + e^G/e)$
0.72	0.20	0.01	1.00

Table 3 presents the values of the resulting parameters.

Table 3: Calibrated parameter values II

	Energy parameters	**Target/source**	**Value**
ϵ	Subst. energy and K	Jointly calibrated	0.25
$\bar{E}$	CES energy	Jointly calibrated	2.52
Ω	TFP in e^G	Jointly calibrated	0.04
B	Prod. coef researchers	Jointly calibrated	0.02

The implied elasticity of substitution between traditional inputs and energy, ϵ, is consistent with the value assumed by Hassler et al. (2021). The implied productivity level in green energy production—captured by the parameter Ω in the model—is calibrated to a relatively low value, reflecting the modest scale of observed investment in green capital. As we show later, this calibration plays an important role in shaping the effectiveness of transitional policies based on public investment in green energy.

3 Transitional dynamics

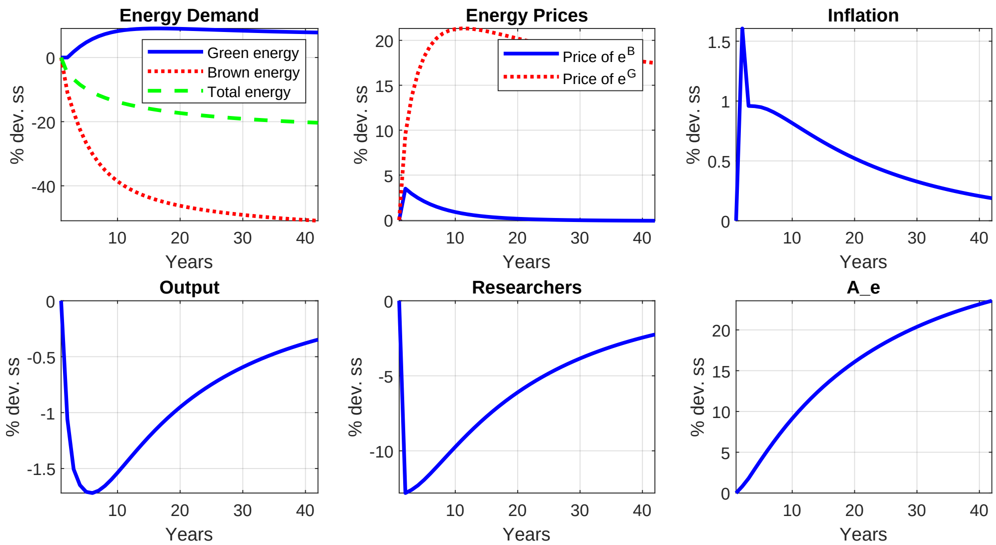
This section presents the quantitative implications of the green transition. We calibrate the initial steady state to Chile, and then, introduce policy changes that initiate a green transition under perfect foresight. This assumption allows us to isolate the pure economic effects of the transition from uncertainty about policy implementation. Our discussion focuses on both the short-run adjustment costs and the long-run benefits of different transition paths.

3.1 A transition induced by increases in brown energy taxes

Following the existing literature, we examine the transitional dynamics driven by increases in brown energy taxes. Our focus on carbon taxation aligns with actual policy, as Chile has made significant climate commitments, including a 2020 update to its Nationally Determined Contribution (NDC) target, aiming for a 45% reduction in CO_2 emissions from 2016 levels by 2030 and carbon neutrality by 2050. In 2014, Chile became the first Latin American country to impose a $5 USD CO_2 tax, targeting emissions and local pollutants. Despite this pioneering move, the carbon tax rate has remained relatively low. Chile's Climate Action Plan 2017–2022 envisions a gradual increase in the tax over time. To capture this transition in our model, we simulate an increase in the excise tax τ^e on the quantity of brown energy used by firms, from 5 to 60 final consumption units over a 200-year horizon. While the model does not explicitly track emissions or carbon content, we assume a proportional relationship between brown energy use and CO_2 emissions. This tax path is calibrated to induce a 45% reduction in brown energy usage in approximately 15 years, broadly consistent with Chile's stated climate goals.[9] Figure 1 illustrates this transition. In the appendix, Figure A.2 presents a larger set of figures that include more variables.

[9] We simulate a 200-period transition; nevertheless, most of the adjustment happens in the first 15 years, in line with the Chilean goals.

Figure 1: Transitional dynamics: Increases in brown energy taxes



Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Variables are in percentage deviations from the initial steady state.

Higher taxes on brown energy increase marginal costs for intermediate firms, fueling inflation in the short and medium term. The rise in carbon taxes increases the after-tax domestic prices of brown energy, and shifts demand toward green energy, gradually pushing up its prices as well, amplifying inflationary pressures. Over time, however, inflation moderates as firms allocate more researchers to improving energy efficiency, enhancing overall energy productivity. In the new equilibrium, the use of brown energy declines by approximately 50%, total energy consumption drops by 20%, and energy efficiency improves by 23%, due to the strategic reallocation of researchers within firms to enhance energy-saving measures in the short term.

The reallocation of researchers during the transition period slows the productivity growth of traditional inputs, damping physical capital accumulation. In the short run, the complementarity between energy and traditional inputs, combined with the inertia in improving energy efficiency and rising costs of brown energy, renders the green transition recessionary. Anticipating long-term increases in brown energy taxation, firms adjust their production by scaling back on traditional inputs, particularly reducing investment demand, which triggers a short-term recession. These recessionary dynamics lead to real currency depreciation and a widening of the country spread, reducing consumption demand. On the other hand, higher tax revenues from brown energy taxes alleviate the government's real debt burden, offsetting some of the adverse effects.

The model predicts persistent "greenflation" with transitory output costs. Inflationary effects are tempered because the decline in investment and consumption demand offsets the inflationary pressures arising from higher marginal costs driven by increased carbon taxes.

The small open economy structure amplifies transitional dynamics through several key channels. Since the domestic economy takes world prices as given, any real depreciation—driven by weaker investment or fiscal imbalances—directly raises the domestic price of imported brown energy. Rising fiscal deficits also elevate the country risk premium, increasing the cost of foreign borrowing and further suppressing consumption and investment. These openness-related effects intensify the trade-offs of the green transition, making macroeconomic adjustment more costly than in a closed economy.

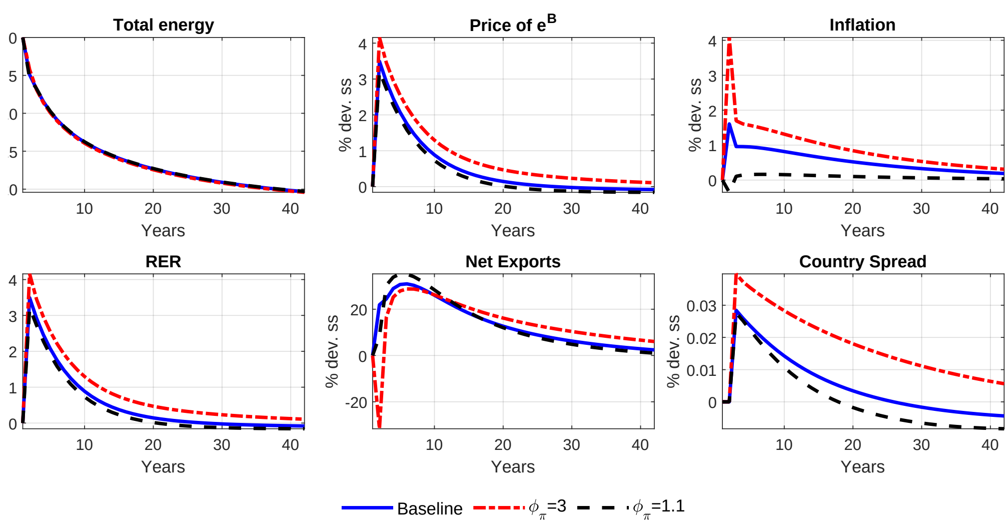
3.2 The role of monetary policy

Monetary policy can affect the greenflationary dynamic described in the previous section. In our benchmark calibration, following Martínez et al. (2020), we set the Taylor rule inflation coefficient to 1.25. In Figure 2, we compare this baseline with two alternative scenarios: a more accommodative stance (inflation coefficient of 1.1) and a more aggressive response to inflation (inflation coefficient of 3.0).

In the standard three-equation model, labor supply is elastic but the model abstracts from investment, so monetary policy affects the economy through labor supply. In our economy, labor supply is inelastic, so this channel is shut off, and monetary policy affects the dynamics through capital accumulation, as well as consumption and output. Under a more accommodative policy, production decreases more due to a larger increase in brown energy prices, which exacerbates inflationary supply-side effects of carbon taxes, fueling "greenflation." In response, firms reallocate researchers toward energy efficiency at the cost of traditional productivity, leading to a reduction in investment demand.

Monetary policy choices impact the external balance during the green transition. A looser policy leads to a higher real depreciation, affecting the country's interest rate spread. More importantly, it influences fiscal space: a looser stance increases brown energy prices through a higher real exchange rate depreciation, boosting revenues from carbon taxes and reducing the debt-to-GDP ratio, albeit with higher inflation. This illustrates the key interaction between monetary and fiscal policies in our model, which is absent in the standard New Keynesian framework.

Figure 2: Transitional dynamics: The role of monetary policy



Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; black discontinuous lines are the case of $\phi_\pi = 3$; and red dashed lines are the case of $\phi_\pi = 1.1$. Variables are in percentage deviations from the initial steady state.

In our setup, monetary policy can mitigate inflationary pressures without exacerbating output losses, even in the presence of carbon taxes, a result in line with optimal-policy findings by Nakov and Thomas (2023). However, a more accommodative monetary policy can yield fiscal benefits by reducing the debt-to-GDP ratio, albeit at the cost of elevated inflation.

3.3 Sensitivity Analysis

In the appendix, we run several sensitivity exercises to assess the robustness of the results. Overall, our sensitivity analysis underscores the importance of tailoring green transition policies to each economy's specific characteristics, particularly on the supply side. These factors crucially influence both the transitional dynamics and the long-term success of the transition. For instance, our model shows that if R&D is ineffective at improving energy efficiency, or if green and brown energy are poorly substitutable in production, Chile is unlikely to achieve its 2030 targets for reducing brown energy use. At the same time, policymakers must carefully consider the additional costs associated with accelerated transition pathways when designing environmental policies. Results are in A.5.

4 Alternative fiscal policy tools

Having analyzed carbon taxation—a policy tool heavily emphasized in the existing literature—we now turn to alternative strategies for reducing greenhouse gas emissions. Although studies such as Timilsina (2022) classify climate policies into three broad categories: fiscal / price instruments, regulatory measures, and direct public investment, we focus on two specific alternatives to carbon taxes: green subsidies and public investment in green infrastructure. These instruments present different trade-offs between transition costs and emissions reduction effectiveness.

A key finding of our analysis is that, when used in isolation, both instruments require unrealistically large values to achieve the targeted transition. Figure A.7 in the Appendix illustrates the resulting transition when either green subsidies or public investment alone are scaled to achieve a 45% reduction in brown energy use in 15 years. Achieving this goal would require subsidies to increase from 0 to 400%, and public green investment to rise to 12.5% of GDP. Financing such measures would lead to substantial increases in public debt, rising by 600% and 200%, respectively, in the small open economy. Thus, achieving the green transition targets using either instrument in isolation is clearly unrealistic.

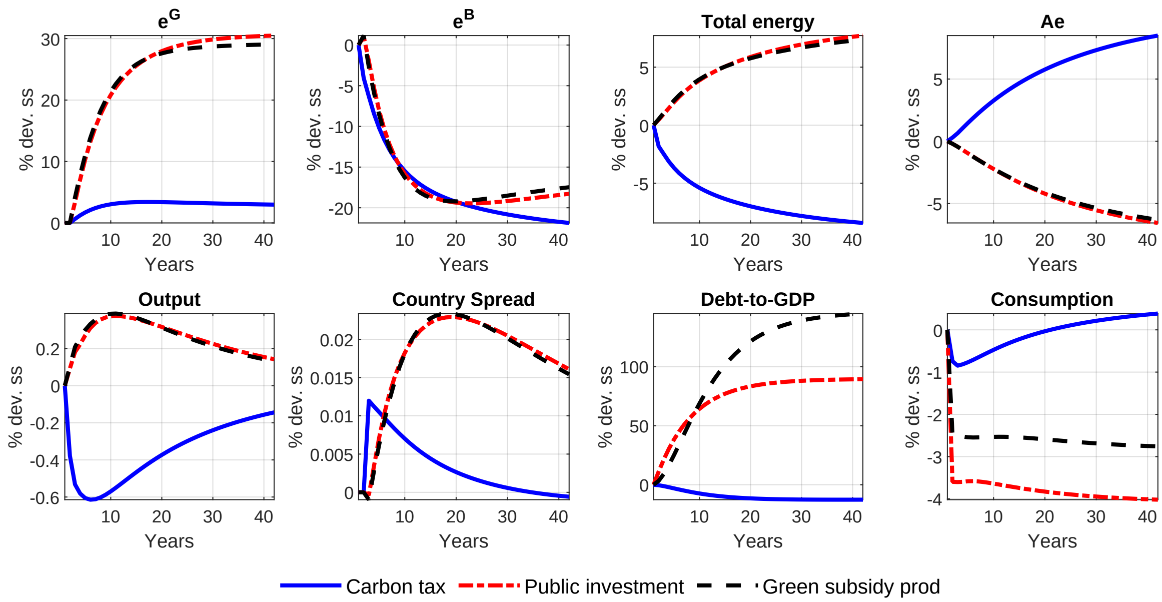
To facilitate comparison across fiscal tools and better understand their mechanisms, we simulate a moderate scenario in which the excise tax nearly quadruples—from 5 in the initial steady state to 22.5 over a 200-year horizon. In another scenario, subsidies rise to 100%, and in third scenario public green investment increases to 3% of GDP. Each of these measures result in a comparable reduction in brown energy use, approximately 17%, after 15 years.

4.1 Green subsidies

While subsidies are often politically preferred to taxes as a fiscal tool, their effectiveness in driving the green transition and their associated fiscal costs are not well understood. Figure 3 depicts a transition where subsidies gradually increase over a 200-year period, starting from zero in the initial steady state and reaching 100% in the new steady state with black dashed lines. Green subsidies drive green energy adoption and, somewhat counterintuitively, lower the prices of both green and brown energy. This price effect prompts firms to reallocate researchers toward enhancing traditional TFP production. While green capital crowds out traditional capital in the short term, over the long run, the improved efficiency of traditional inputs drives a surge in investment. Consequently, subsidies act as a positive supply shock, leading to lower inflation and output gains and a real exchange rate appreciation.

However, this approach entails substantial costs. The debt-to-GDP ratio rises sharply, increasing by 200% in the new steady state. This fiscal expansion triggers a surge in country risk premiums, and, combined with higher lump-sum taxes under the fiscal rule, leads to

Figure 3: Transition using different fiscal instruments



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 22.5 final consumption units (blue continuous lines); subsidies change from 0 to 100% (black discontinuous lines); and public investment changes from 0 to 3% of GDP (red dashed lines).Variables are in percentage deviations from the initial steady state.

a sustained decline in private consumption. While increased green subsidies contribute to a medium-run reduction in brown energy use, over the long term the economy settles into a new steady state with higher brown energy consumption. This occurs because subsidies lower energy prices, weakening incentives to improve energy efficiency. Thus, despite their political appeal, green subsidies are less effective at enhancing long-run energy efficiency and may impose heavier burdens on consumers in small open economies compared to carbon taxes.

4.2 Public green investment

An alternative approach to promoting the green transition is through green public investment. For example, the German government plans to accelerate the transition by investing in green infrastructure. Former Finance Minister Christian Lindner recently announced a €200 billion initiative (2022–2026) to fund industrial transformation, including climate protection, hydrogen technology, and electric vehicle charging networks. At the same time, Germany aims to increase investment in renewable energy production.

To evaluate this approach, we simulate a scenario where public investment in green infrastructure rises from near-zero to 3% of GDP. We illustrate this transition in Figure 3. The surge in green public investment crowds out green private investment, as we assume the two are substitutes in green energy production.[10] Within the green energy sector's production framework, the rise in green public capital enhances the sector's productivity, leading to a decline in green energy prices and an increase in its usage. As cheaper green energy replaces brown energy, overall energy costs for firms decrease. This shift prompts firms to allocate more resources toward improving the TFP of traditional factors, reallocating researchers to enhance the energy efficiency of traditional inputs. As energy efficiency deteriorates, overall energy consumption increases. Similar to the case with green subsidies, the economy settles into a new steady state where the reduction in brown energy use is smaller than under a carbon tax-driven transition.

The productivity growth of traditional factors fuels higher capital investment and output, while the drop in energy prices lowers inflation. However, the fiscal costs associated with such a policy are significant. Similar to the case of subsidies, though to a lesser extent, the debt-to-GDP ratio increases substantially, leading to a persistent surge in the country spread. The higher debt burden, coupled with implied increases in lump-sum taxes and elevated demand for capital, results in considerable and sustained crowding out of private consumption.

Hence, our analysis suggests that while these policies are not inflationary and entail lower output costs during the transition, they are less effective in reducing brown energy use

[10] In Appendix Figure A.8, we explore the scenario where the two inputs are complements. In that case, green public investment becomes a more effective fiscal policy tool, encouraging firms to invest more in green capital and further reducing brown energy usage.

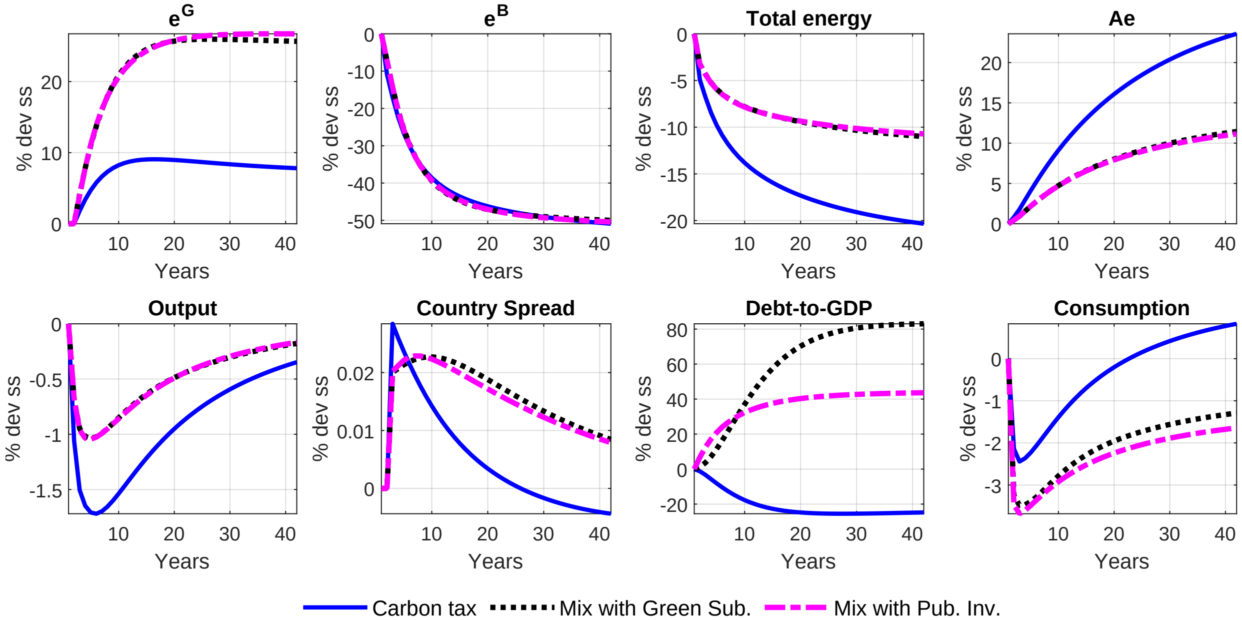
and impose substantial fiscal burdens. To avoid adverse effects on private consumption, they must be paired with measures that alleviate fiscal pressure in small open economies.

4.3 Fiscal policy mix

Public opposition to carbon taxation is well-documented in the literature. For instance, Carattini et al. (2018) identify key concerns including personal costs, regressivity, negative economic impacts, inefficiency, and the self-interest of the state. Given these political challenges and our previous findings about the costs and benefits of individual policies, we explore whether policy combinations might achieve emissions reductions more effectively. Specifically, we examine scenarios where more moderate carbon tax increases help finance either green subsidies or public green investment.

Figure 4 presents two policy experiments targeting the same reduction in brown energy use as our baseline scenario. The first experiment, shown with black dotted lines, combines a moderate increase in the excise tax on brown energy inputs (from 5 to 45 final consumption units) with green subsidies rising from 0% to 60%. The second experiment, represented by dashed magenta lines, pairs the same tax increase with public investment in green capital (rising from 0% to 2% of GDP). These combinations demonstrate how mixed approaches can achieve environmental goals while mitigating the drawbacks of individual policies.

Figure 4: Transition with fiscal policy mix



Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 60 final consumption units (blue continuous lines); carbon taxes increase from 5 to 45 units and green subsidies rise from 0% to 60% (black discontinuous lines); carbon taxes increase from 5 to 45 units and public investment in green capital increases from 0% to 2% of GDP (magenta discontinuous lines). Carbon taxes, green subsidies, and public green investment are in levels. The rest of the variables are in percentage deviations from the initial steady state.

Given the dynamics of the pure policies (represented in Figure 3), it is unsurprising that both policy mixes are associated with lower short-run output and inflation losses as well as a lighter fiscal burden in terms of debt-to-GDP ratio increases and bond spreads. Specifically, debt-to-GDP increases by 40% under the green public investment mix and by 80% under the green subsidy mix. In general, the use of additional fiscal tools leads to similar increases in green energy consumption and higher consumption losses, as the effects of mixed policies on debt-to-GDP and spreads remain operative. We examine the welfare implications of these policy combinations in the following section.

5 The welfare costs of the green transition

A natural metric for ranking alternative policy choices is their impact on welfare. Although our model abstracts from the negative externalities associated with brown energy use, welfare comparisons remain valid for evaluating different policy instruments. What we emphasize in this section is that the welfare implications of the transition critically depend on the specific combination of policy instruments and fiscal choices considered.

In this section, we calculate the welfare costs of the green transition in different transition scenarios. First, we recover the trend along the transitions using (A.1) and (A.2):

$$X_t = \tilde{A}_t \tilde{k}_t^{\alpha} X_{t-1},$$

for a given initial condition X_0, common to all scenarios. Without loss of generality, we normalize $X_0 = 1$. Second, we recover the path of consumption in levels along the transition

$$c_t = \tilde{c}_t X_{t-1},$$

where $\tilde{c}_t$ is the detrended value of consumption.

We calculate welfare using a consumption equivalence measure. We adopt as a benchmark the consumption in the initial steady state and compute how much consumers are willing to give up on the initial steady-state consumption to reach a level of welfare along the transition that is comparable to their initial steady state; that is,

$$W_k = \sum_{t=1}^{T} \beta^t ln\left(c_{t,k} + \Lambda_k\right), \tag{19}$$

with

$$W_k = \sum_{t=1}^{T} \beta^t ln\left(c_{0,k}\right), \tag{20}$$

where T is equal to 200 periods, the length of the transition. k is the correspondent scenario: i) an increase in carbon taxes from 5 to 60 final consumption units; ii) a policy mix with increases in brown taxes from 5 to 45 final consumption units and of green subsidies from zero to 60%; and iii) a policy mix with increases in brown taxes from 5 to 45 final

Table 4: Welfare comparisons

Policy scenario k	**Welfare Loss**
Carbon tax rise from 5 to 60	8.18%
Carbon tax rise from 5 to 42.5 - subsidy of 65%	7.33%
Carbon tax rise from 5 to 42.5 - green capital rise by 2.5% of GDP	7.65%

Note: Losses are in percentage deviations from initial steady state consumption.

consumption units and of green public investment from zero to 2% of GDP. Notice $c_{0,k}$ is the consumption level at the initial steady state, and it is the same for all k.

The value of Λ_k determines the welfare gains or losses compared to the initial steady state. Positive values of Λ_k imply that consumers are worse off along the transition to the new steady state than with the initial steady-state consumption level, and negative values, instead, represent welfare improvements.

Table 4 presents the losses in percentage deviations from initial steady state consumption for the three scenarios considered. The green transition proves costly in terms of welfare, as we have not included factors in the utility function—such as health benefits or survival probability—that could make the transition more beneficial for the agents in our model economy.

Among the fiscal policy strategies considered, raising carbon taxes alone results in the highest welfare costs. Our model incorporates endogenous growth, meaning fiscal policy choices influence not only short-run dynamics but also the economy's long-run growth path. While green subsidies and public investment tend to crowd out private consumption in the short term, they increase trend growth over time, ultimately benefiting household welfare. As a result, mixed policy strategies—combining moderate carbon tax increases with subsidies or public green investment—improve welfare by balancing short-term adjustment costs with long-term efficiency gains. This finding is robust across specifications, although the precise welfare ranking depends on the parameterization of green energy production, particularly the substitutability between private and public green capital, and their relative shares in total green energy output.[11]

6 Conclusions

We analyze the transitional dynamics of a green transformation in an emerging small open economy, focusing on the role of fiscal policy and the effectiveness of key instruments: carbon taxes, green subsidies, and public investment. Our findings show that carbon taxes effectively reduce brown energy use and improve energy efficiency but lead to short-term output losses and persistent "greenflation." In contrast, green subsidies and public investment fail to deliver comparable reductions under realistic fiscal constraints. These policies trigger substantial fiscal shocks, raising sovereign risk premiums and borrowing costs, which in turn amplify short-term consumption losses—especially in economies with limited access to external financing.

Monetary policy can help contain inflationary pressures in the short run, but it has limited ability to offset the real costs of the transition. The magnitude and persistence of these trade-offs depend critically on structural features of the economy, especially those affecting the supply side, such as substitutability between inputs, endogenous energy efficiency, and nominal rigidities.

Our analysis highlights the benefits of mixed policy strategies that recycle revenues from carbon taxes into green subsidies or public investment. Such combinations can deliver similar environmental outcomes at a lower welfare cost, while easing the fiscal burden associated with standalone interventions. These results underscore the importance of tailoring green transition strategies to the characteristics and constraints of small open economies.

[11] For instance, when public and private green capital are complements, public investment is particularly effective, as it supports private activity without crowding out consumption. See Figure A.8 for transitional dynamics under this assumption.

It is important to note that our analysis assumes perfect foresight and full credibility in fiscal policy implementation. Future research should explore the implications of uncertainty, commitment problems, and heterogeneous household responses for the design and political economy of green transition policies.

In sum, there is no single optimal path to a sustainable energy future for small open economies. Policymakers must carefully balance environmental goals with macroeconomic stability, fiscal space, and political feasibility.

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A Appendix

A.1 Equilibrium equations

A.1.1 Household

$$\lambda_t = c_t^{-\sigma}$$

$$k_{t+1} = (1-\delta)k_t + i_t - \frac{\kappa}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2 k_t$$

$$\lambda_t \frac{1}{P_t} = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1} R_t}{P_{t+1}}\right]$$

$$\lambda_t = \beta \mathbb{E}_t \left[\lambda_{t+1} \frac{R_t^*}{\pi_t^*} \frac{rer_{t+1}}{rer_t} \varphi_{t+1}^A (\tilde{A}_{t+1}^f)\right]$$

$$\lambda_t q_t \left(1 + \kappa\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)\right) = \beta \mathbb{E}_t \left[\lambda_{t+1} \frac{R_{t+1}^k}{P_{t+1}} + \lambda_{t+1} q_{t+1} \left(1 - \delta + \left(\kappa\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)\frac{k_{t+2}}{k_{t+1}} - \frac{\kappa}{2}\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)^2\right)\right)\right]$$

$$s_{t+1}^G = (1-\delta)\, s_t^G - \Phi_s(s_{t+1}^G, s_t^G) s_t^G + i_t^G$$

$$\lambda_t q_t^G \left(1 + \kappa\left(\frac{s_{t+1}^G}{s_t^G} - \bar{g}\right)\right) = \beta \mathbb{E}_t \left[\lambda_{t+1} \frac{R_{t+1}^s}{P_{t+1}} + \lambda_{t+1} q_{t+1}^G \left(1 - \delta + \left(\kappa\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)\frac{s_{t+2}^G}{s_{t+1}^G} - \frac{\kappa}{2}\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)^2\right)\right)\right]$$

$$\lambda_t q_t^G = \lambda_t$$

$$p_{H,t} y_{H,t} = c_t + g_{H,t} + i_t + i_t^G + i_t^{G,P} + \frac{\iota_{PH}}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t} y_{H,t} + nx_t - p_t^B e_t^{B,*}$$

A.1.2 Intermediate goods producers

$$y_{H,t} = \left[\left(A_t k_t^\alpha \bar{h}^{(1-\alpha)}\right)^{\frac{\epsilon-1}{\epsilon}} + (A_{e,t} e_t)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$e_t = \bar{E}\left[(1-\zeta)\left(e_t^G\right)^{\xi} + \zeta\left(e_t^B\right)^{\xi}\right]^{\frac{1}{\xi}}$$

$$r_t^k = mc_t y_{H,t}^{1/\epsilon}\left(A_t k_t^{\alpha}\bar{h}^{1-\alpha}\right)^{-1/\epsilon} A_t \alpha k_t^{\alpha-1}\bar{h}^{1-\alpha}$$

$$w_t = mc_t y_{H,t}^{1/\epsilon}\left(A_t k_t^{\alpha}\bar{h}^{1-\alpha}\right)^{-1/\epsilon} A_t(1-\alpha) k_t^{\alpha}\bar{h}^{-\alpha}$$

$$p_t^G = mc_t y_{H,t}^{1/\epsilon}\left(A_{e,t}e_t\right)^{-1/\epsilon} A_e(1-\zeta)\left(\frac{e_t}{e_t^G}\right)^{1-\xi}$$

$$p_t^B + \tau_t^e = mc_t y_{H,t}^{1/\epsilon}\left(A_{e,t}e_t\right)^{-1/\epsilon} A_e\zeta\left(\frac{e_t}{e_t^B}\right)^{1-\xi}$$

$$\pi_{H,t}\left(\pi_{H,t}-\bar{\pi}_H\right) = \beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi_{H,t+1}^2\left(\pi_{H,t+1}-\bar{\pi}_H\right)\frac{y_{H,t+1}}{y_{H,t}}\right] + \frac{\varepsilon_{Pt}}{\iota_{PH}}\left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_{Pt}-1}{\varepsilon_{Pt}}\right)$$

$$\mu_{A,t}Bn_t^{\phi-1}A_{t-1} = \mu_{A_e,t}B_e(1-n_t)^{\phi-1}A_{e,t-1}$$

$$\mu_{A,t} = \beta\frac{\lambda_{t+1}}{\lambda_t}(1+Bn_{t+1}^{\phi})\mu_{A,t+1} + mc_t y_{h,t}^{1/\epsilon}(A_t k_{t-1}^{\alpha}H^{1-\alpha})^{-1/\epsilon}k_{t-1}^{\alpha}H^{1-\alpha}$$

$$\mu_{A_e,t} = \beta\frac{\lambda_{t+1}}{\lambda_t}(1+B_e(1-n_{t+1})^{\phi})\mu_{A_e,t+1} + mc_t y_{h,t}^{1/\epsilon}A_{e,t}^{-1/\epsilon}e_t^{(\epsilon-1)/\epsilon}$$

A.1.3 Green energy producer

$$e_t^G = \Omega L^{1-\eta}[(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\eta/\omega)}$$

$$\Omega L^{1-\eta}\eta[(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\eta/\omega)-1}(1-\gamma)\eta(s_t^G)^{\omega-1} = \frac{R_t^s}{(1+s_t^{P_e})P_t^G}$$

A.1.4 Brown energy sector

$$p_t^B = rer_t p_t^{B,*}$$

A.1.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R}\left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi}\left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}$$

$$\tau_t + \tau_t^e e_t^b + b_{t+1} = s_t^{P_e}p_t^G e_t^G + \frac{b_t}{\pi_t}R_{t-1} + i_t^{G,P} + g_{H,t}$$

$$\tau_t - \tau^* = \phi_\tau b_{t-1}.$$

A.1.6 Definitions

$$1 = \left[(1-\chi)(p_{H,t})^{1-\theta} + \chi(rer_t)^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

$$nx_t = rer_t b^*_{t+1} - rer_t \frac{b^*_t}{\pi^*_t} R^*_{t-1} \Psi^A \left(\tilde{A}^f_t\right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \pi_t$$

$$y_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(c_t + g_{H,t} + i_t + s^G_t + i^{G,P}_t\right) + c^*_{H,t}$$

$$c^*_{H,t} = \left(\frac{P^*_{H,t}}{rer_t}\right)^{-\theta^*} y^*_t$$

$$\frac{A_t}{A_{t-1}} = 1 + Bn_t^\phi$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e(1-n_t)^\phi$$

$$X_t = A_t k_t^\alpha$$

$$e^{B,*}_t = e^B_t - e^{B,d}_t$$

A.2 Balance growth path assumptions

As mentioned earlier, the directed technical change affects the long-run energy share and economic growth (see also Hassler et al. (2021)). Specifically, let X_{t-1} represent the output trend during period t, which is the growth rate of $y_{H,t}$. We define

$$X_t = A_t k_t^\alpha \tag{A.1}$$

such that

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^\alpha}{X_{t-1}^{1-\alpha} X_{t-1}^\alpha} = \tilde{A}_t \tilde{k}_t^\alpha \tag{A.2}$$

is the growth rate of the economy. Since the stock of capital's trend is X_{t-1}, its productivity factor A_t grows at $X_{t-1}^{1-\alpha}$. $\tilde{A}_t$ and $\tilde{k}_t$ are the stationarized counterparts of A_t and k_t, respectively.

To have a balanced growth path, the two additive components of the production function must grow at the same rate, given its functional form. This requirement implies that

$$X_{t-1} = X_{t-1}^{Ae} X_{t-1}^{e},$$

and, from equation (9),

$$X_t^e = X_t^{eG} = X_t^{eB}.$$

Thus, all energy sources grow at the same rate for every period t. Then, from the production function of green energy, we get the following condition:

$$X_{t-1}^{eG} = X_{t-1}^{\eta}.$$

Hence,

$$X_{t-1}^{eB} = X_{t-1}^{e} = X_{t-1}^{\eta}$$

and

$$X_{t-1}^{Ae} = X_{t-1}^{1-\eta}.$$

Finally, from the first-order condition of intermediate producers to energy inputs, prices P_t^G and P_t^B grow at $X_{t-1}^{1-\eta}$.

A.3 Stationarized equilibrium equations

Define X_{t-1} as the GDP trend, and define: $g_t = \frac{X_t}{X_{t-1}}$ as the growth rate. We assume variables at t are stationarized by X_{t-1}. For instance, $\tilde{c}_t = \frac{c_t}{X_{t-1}}$.

Define: $\tilde{\lambda}_t = \frac{\lambda_t}{X_{t-1}^{-\sigma}}$.

In this section, we present the stationarized equilibrium equations.

A.4 Equilibrium equations

A.4.1 Household

$$\tilde{\lambda}_t = \tilde{c}_t^{-\sigma}$$

$$g_t \tilde{k}_{t+1} = (1-\delta)\tilde{k}_t + \tilde{i}_t - \frac{\kappa}{2}\left(\frac{\tilde{k}_{t+1} g_t}{\tilde{k}_t} - \bar{g}\right)^2 \tilde{k}_t$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma} \mathbb{E}_t \left[\frac{\tilde{\lambda}_{t+1} R_t}{\pi_{t+1}}\right]$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma} \mathbb{E}_t \left[\tilde{\lambda}_{t+1} \frac{R_t^*}{\pi_t^*} \frac{rer_{t+1}}{rer_t} \varphi_{t+1}^A (\tilde{A}_{t+1}^f)\right]$$

$$\tilde{\lambda}_t q_t \left(1 + \kappa\left(\frac{\tilde{k}_{t+1} g_t}{\tilde{k}_t} - \bar{g}\right)\right) = \beta g_t^{-\sigma} \mathbb{E}_t \Bigg[\tilde{\lambda}_{t+1} r_{t+1}^k + \tilde{\lambda}_{t+1} q_{t+1} \Bigg(1 - \delta + \Bigg(\kappa\left(\frac{\tilde{k}_{t+2} g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)\frac{\tilde{k}_{t+2} g_{t+1}}{\tilde{k}_{t+1}} - \frac{\kappa}{2}\left(\frac{\tilde{k}_{t+2} g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)^2\Bigg)\Bigg)\Bigg]$$

$$g_t \tilde{s}_{t+1}^G = (1-\delta)\tilde{s}_t^G + \tilde{i}_t^G - \frac{\kappa}{2}\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)^2 \tilde{s}_t^G$$

$$\tilde{\lambda}_t q_t^G \left(1 + \kappa\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)\right) = \beta g_t^{-\sigma} \mathbb{E}_t \Bigg[\tilde{\lambda}_{t+1} r_{t+1}^s + \tilde{\lambda}_{t+1} q_{t+1}^G \Bigg(1 - \delta + \Bigg(\kappa\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \frac{\kappa}{2}\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)^2\Bigg)\Bigg)\Bigg]$$

$$p_{H,t}\tilde{y}_{H,t} = \tilde{c}_t + \tilde{g}_{H,t} + \tilde{i}_t + \tilde{i}^G_t + \tilde{i}^{G,P}_t + \frac{\iota_{PH}}{2}\left(\pi^H_t - \bar{\pi}^H_t\right)^2 p_{H,t}\tilde{y}_{H,t} + \tilde{nx}_t - \tilde{p}^B_t e^{B,*}_t$$

A.4.2 Intermediate goods producers

$$\tilde{y}_{H,t} = \left[\left(\tilde{A}_t\tilde{k}^\alpha_t\bar{h}^{(1-\alpha)}\right)^{\frac{\epsilon-1}{\epsilon}} + \left(\tilde{A}_{e,t}\tilde{e}_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$\tilde{e}_t = \bar{E}\left[(1-\zeta)\left(\tilde{e}^G_t\right)^\xi + \zeta\left(\tilde{e}^B_t\right)^\xi\right]^{\frac{1}{\xi}}$$

$$r^k_t = mc_t\tilde{y}^{1/\epsilon}_{H,t}\left(\tilde{A}_t\tilde{k}^\alpha_t\bar{h}^{(1-\alpha)}\right)^{-1/\epsilon}\tilde{A}_t\alpha\tilde{k}^{\alpha-1}_t\bar{h}^{(1-\alpha)}$$

$$\tilde{w}_t = mc_t\tilde{y}^{1/\epsilon}_{H,t}\left(\tilde{A}_t\tilde{k}^\alpha_t\bar{h}^{(1-\alpha)}\right)^{-1/\epsilon}\tilde{A}_t(1-\alpha)\tilde{k}^\alpha_t\bar{h}^{-\alpha}$$

$$\tilde{p}^G_t(1-s^{P_e}_t) = mc_t\tilde{y}^{1/\epsilon}_{H,t}\left(\tilde{A}_{e,t}\tilde{e}_t\right)^{-1/\epsilon}\tilde{A}_{e,t}(1-\zeta)\left(\frac{\tilde{e}_t}{\tilde{e}^G_t}\right)^{1-\xi}$$

$$\tilde{p}^B_t + \tilde{\tau}^e_t = mc_t\tilde{y}^{1/\epsilon}_{H,t}\left(\tilde{A}_{e,t}\tilde{e}_t\right)^{-1/\epsilon}\tilde{A}_{e,t}\zeta\left(\frac{\tilde{e}_t}{\tilde{e}^B_t}\right)^{1-\xi}$$

$$\pi_{H,t}\left(\pi_{H,t} - \bar{\pi}_H\right) = \beta\mathbb{E}_t\left[\frac{\lambda_{t+1}}{\lambda_t}\pi^2_{H,t+1}\left(\pi_{H,t+1} - \bar{\pi}_H\right)\frac{\tilde{y}_{H,t+1}}{\tilde{y}_{H,t}g_t}\right] + \frac{\varepsilon_{Pt}}{\iota_{PH}}\left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_{Pt}-1}{\varepsilon_{Pt}}\right)$$

$$\mu_{A,t}g^\alpha_{t-1}Bn^{\phi-1}_t A_{t-1} = \mu_{A_e,t}B_e(1-n_t)^{\phi-1}g^\mu_{t-1}A_{e,t-1}$$

$$\mu_{A,t} = \beta\frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t}g^{-\sigma}_t(1+Bn^\phi_{t+1})\mu_{A,t+1}g^\alpha_t + mc_t\tilde{y}^{1/\epsilon}_{h,t}(\tilde{A}_t\tilde{k}^\alpha_{t-1}\bar{h}^{(1-\alpha)})^{-1/\epsilon}\tilde{k}^\alpha_{t-1}\bar{h}^{(1-\alpha)}$$

$$\mu_{A_e,t} = \beta\frac{\tilde{\lambda}_{t+1}}{\tilde{\lambda}_t}g^{-\sigma}_t(1+B_e(1-n_{t+1})^\phi)\mu_{A_e,t+1}g^\mu_t + mc_t\tilde{y}^{1/\epsilon}_{h,t}\tilde{A}^{-1/\epsilon}_{e,t}\tilde{e}^{(\epsilon-1)/\epsilon}_t$$

A.4.3 Green energy producer

$$^G_t = \Omega L^{1-\eta}[(1-\gamma)(\tilde{s}^G_t)^\omega + \gamma(\tilde{s}^{G,P}_t)^\omega]^{(\eta/\omega)}$$

$$\Omega L^{1-\eta}\eta[(1-\gamma)(\tilde{s}^G_t)^\omega + \gamma(\tilde{s}^{G,P}_t)^\omega]^{(\eta/\omega)-1}(1-\gamma)\eta(\tilde{s}^G_t)^{\omega-1} = \frac{r^s_t}{\tilde{p}^G_t}$$

A.4.4 Brown energy sector

$$\tilde{p}_t^B = rer_t \tilde{p}_t^{B,*}$$

A.4.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R}$$

$$\tilde{\tau}_t + \tau_t^e \tilde{e}_t^b + \tilde{b}_{t+1} = s_t^{G_e} \tilde{i}_t^G + s_t^{P_e} \tilde{p}_t^G \tilde{e}_t^G + \frac{\tilde{b}_t}{\pi_t} R_{t-1} + \tilde{i}_t^{G,P} + \tilde{g}_{H,t}$$

$$c_{H,t}^* = \left(\frac{P_{H,t}^*}{rer_t}\right)^{-\theta^*} y_t^*$$

A.4.6 Definitions

$$1 = \left[(1-\chi)(p_{H,t})^{1-\theta} + \chi(rer_t)^{1-\theta}\right]^{\frac{1}{1-\theta}}$$

$$\tilde{nx}_t = rer_t \tilde{b}_{t+1}^* g_t - rer_t \frac{\tilde{b}_t^*}{\pi_t^*} R_{t-1}^* \Psi^A \left(\tilde{A}_t^f\right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \pi_t$$

$$\tilde{y}_{H,t} = (1-\chi) p_{h,t}^{-\theta} \left(\tilde{c}_t + \tilde{g}_{H,t} + \tilde{i}_t + \tilde{s}_t^G + \tilde{i}_t^{G,P}\right) + \tilde{c}_{H,t}^*$$

$$\tilde{c}_{H,t}^* = \left(\frac{p_{H,t}^*}{rer_t}\right)^{-\theta^*} \tilde{y}_t^*$$

$$\frac{A_t}{A_{t-1}} = 1 + Bn_t^\phi$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e(1 - n_t)^{\phi}$$

$$g_t = \tilde{A}_t \tilde{k}_t^{\alpha}$$

$$\tilde{e}_t^{B,*} = \tilde{e}_t^{B} - \tilde{e}_t^{B,d}$$

A.5 Sensitivity analysis

The modeling of the supply side is crucial in determining how firms respond to changes in relative energy prices for both the short and long run. The transitional dynamics of the green transformation depend fundamentally on firms' ability to substitute between different energy sources and improve their energy efficiency. Our framework incorporates frictions that can significantly impact the transitional dynamics as well as the initial and final steady states. For this reason, in this subsection we consider various sensitivity exercises.

We start by examining the role of price stickiness, a key friction that affects how changes in carbon taxes translate into price adjustments. As shown in Appendix Figure A.6, stronger price rigidities influence the real exchange rate's response during the transition, given the monetary policy rule, resulting in larger increases in brown energy prices. With more rigid prices, output losses are greater, leading to higher spreads and further reductions in consumption and investment demand.

We next examine how researchers' effectiveness in improving productivity shapes the transition. At the heart of this analysis is the returns to scale parameter in the research sector (ϕ), which governs how researchers' efforts translate into productivity gains. To understand its role, we compare our baseline calibration of ϕ to 0.92 with a lower value of

0.7, representing an environment where researchers face greater difficulties in achieving productivity improvements. The transitional dynamics under this lower effectiveness scenario are shown in red dashed-dotted lines in Figure A.1, with all variables expressed as percentage deviations from their respective steady states, except for the carbon tax, which is shown in levels.

The impact of reduced research effectiveness manifests through both steady-state and transitional channels. In the new steady state, the same increase in carbon taxation leads to an almost ten percent smaller reduction in brown energy use, reflecting firms' diminished ability to adapt through productivity improvements. More striking are the differences in short-run dynamics: inflation increases more sharply and output declines more severely and persistently during the green transition, when researchers cannot effectively achieve productivity improvements.

These amplified short-run costs emerge from firms' constrained ability to adjust through the productivity channel. When researchers are less effective at improving energy efficiency (evidenced by the flatter slope of Ae transition), firms must compensate by increasing their investment in green capital. Furthermore, though firms reallocate fewer researchers when ϕ is low, the productivity loss in the traditional sector is more severe due to researchers' reduced effectiveness. This combination of higher required green investment and larger productivity losses in traditional production amplifies the contractionary effects of carbon taxation, resulting in more pronounced output declines during the transition period.

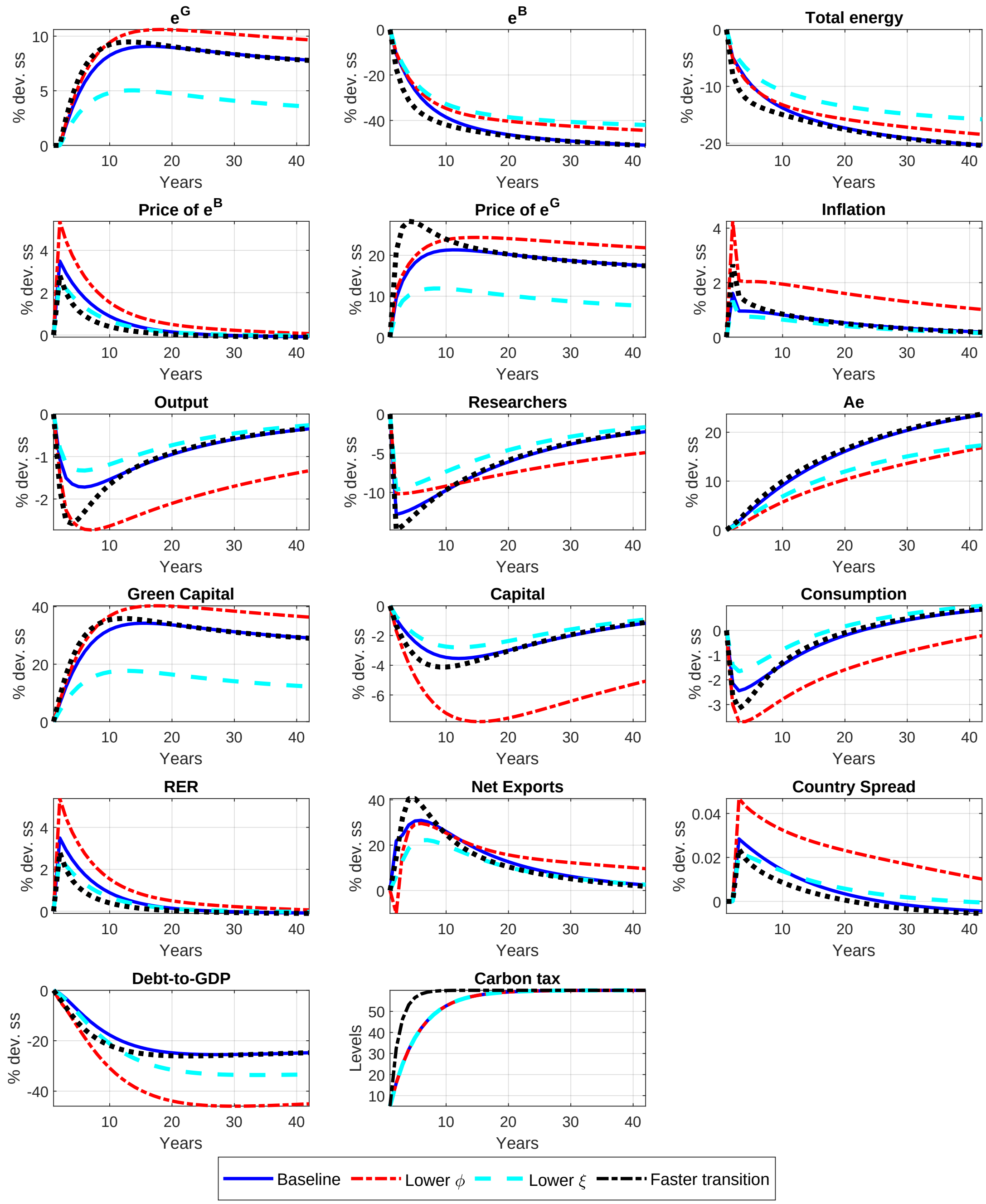
The reduced effectiveness of researchers in improving energy efficiency limits firms' ability to adapt to changes in relative prices. This raises marginal costs in the short run, driving up inflation. The resulting inflationary pressures cause a higher real depreciation and further increases in country spreads, which hurt consumption demand and exacerbate the negative impact on output during the transition.

We also examine how changes in the substitutability between green and brown energy in production influences transitional dynamics. Figure A.1 depicts these dynamics when the substitutability parameter, ξ, is reduced from 0.67 to 0.4 (cyan dashed lines). With low substitutability between energy inputs, higher levels of green energy are ineffective at replacing brown energy, resulting in a smaller decline in brown energy usage over the long term, despite the carbon tax remaining unchanged relative to the baseline scenario.

Firms, recognizing that green energy cannot effectively substitute for brown energy in production, make smaller adjustments to their energy efficiency during the transition. This reduced adaptation manifests in fewer researchers being allocated to the R&D sector, resulting in a smaller reduction in traditional energy input demand and lower output costs in the short term. These effects contribute to a more moderate real depreciation, which limits the rise in brown energy prices. Moreover, the lower demand for green energy moderates its price increase. As a result, the rise in brown energy taxes exerts less pressure on marginal costs, leading to reduced inflationary pressures throughout the green transition. As a result, the transition costs decrease, but so does the effectiveness of the transition itself. With lower substitutability between energy inputs, larger increases in carbon taxes are required to achieve the desired energy goals.

Given ongoing policy discussions around accelerating the green transition in some countries, we assess how the speed of adjustment influences economic outcomes. We compare our baseline scenario, in which carbon taxes reach their steady state over 20 years, with a faster transition completed in 8 years. As shown by the black dotted lines in Figure A.1, a rapid transition intensifies both inflation and output losses. This is because firms must compress their adjustments into a shorter period, prompting more abrupt reallocation of researchers and greater short-term production disruptions. The model indicates that a more gradual transition would better contain greenflation and mitigate output costs.

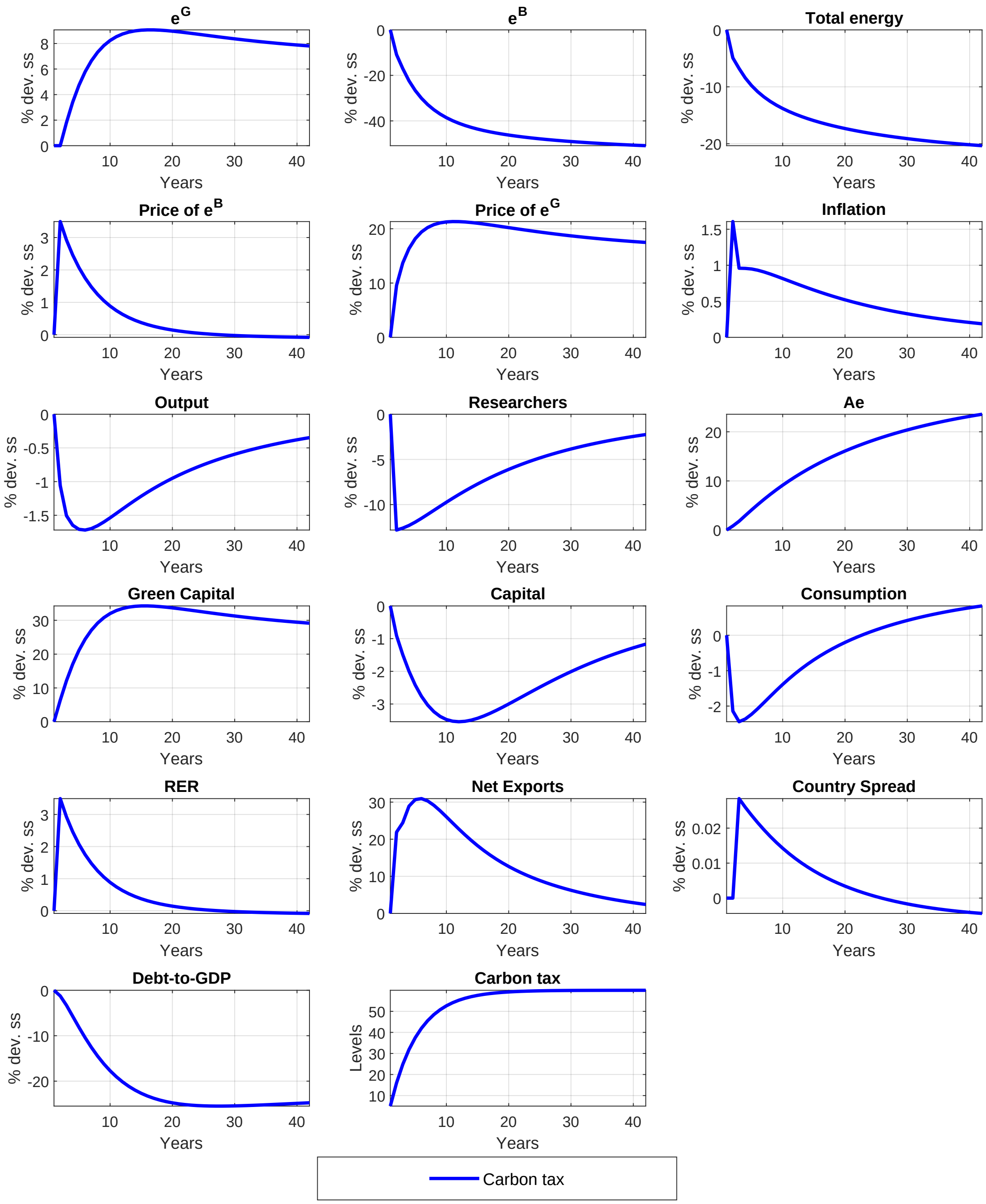
Figure A.1: Transitional dynamics: Sensitivity analysis



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Blue lines represent the baseline calibration; red dashed lines represent the case of $\phi = 0.7$; cyan dashed lines represent the case of $\xi = 0.4$; and dotted black lines represent the case of a transition in which taxes reach the new steady-state value in eight years. Variables are in percentage deviations from the corresponding initial steady state except for taxes.

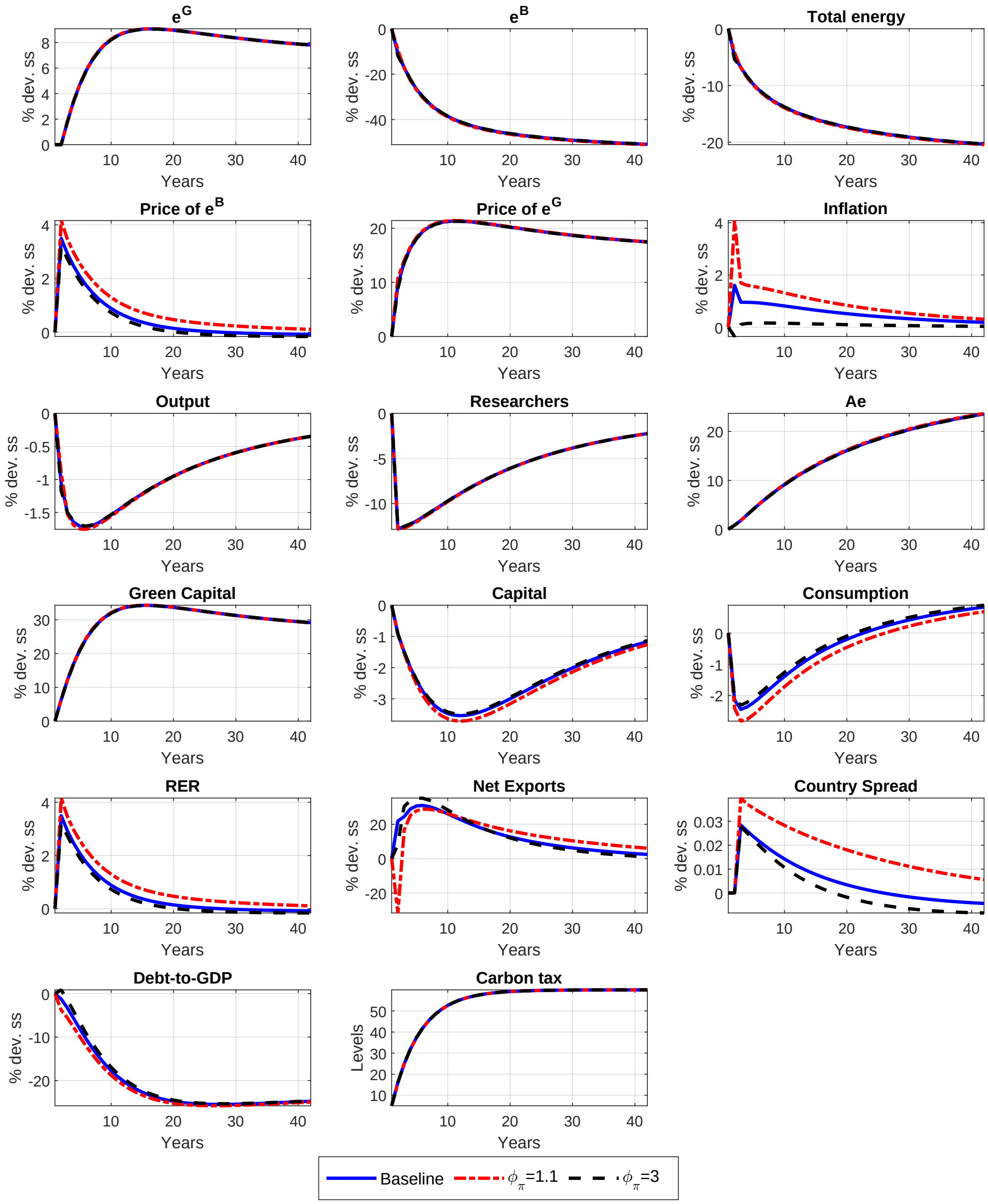
A.6 Full dynamics baseline exercises

Figure A.2: Transitional dynamics: Increases in brown energy taxes



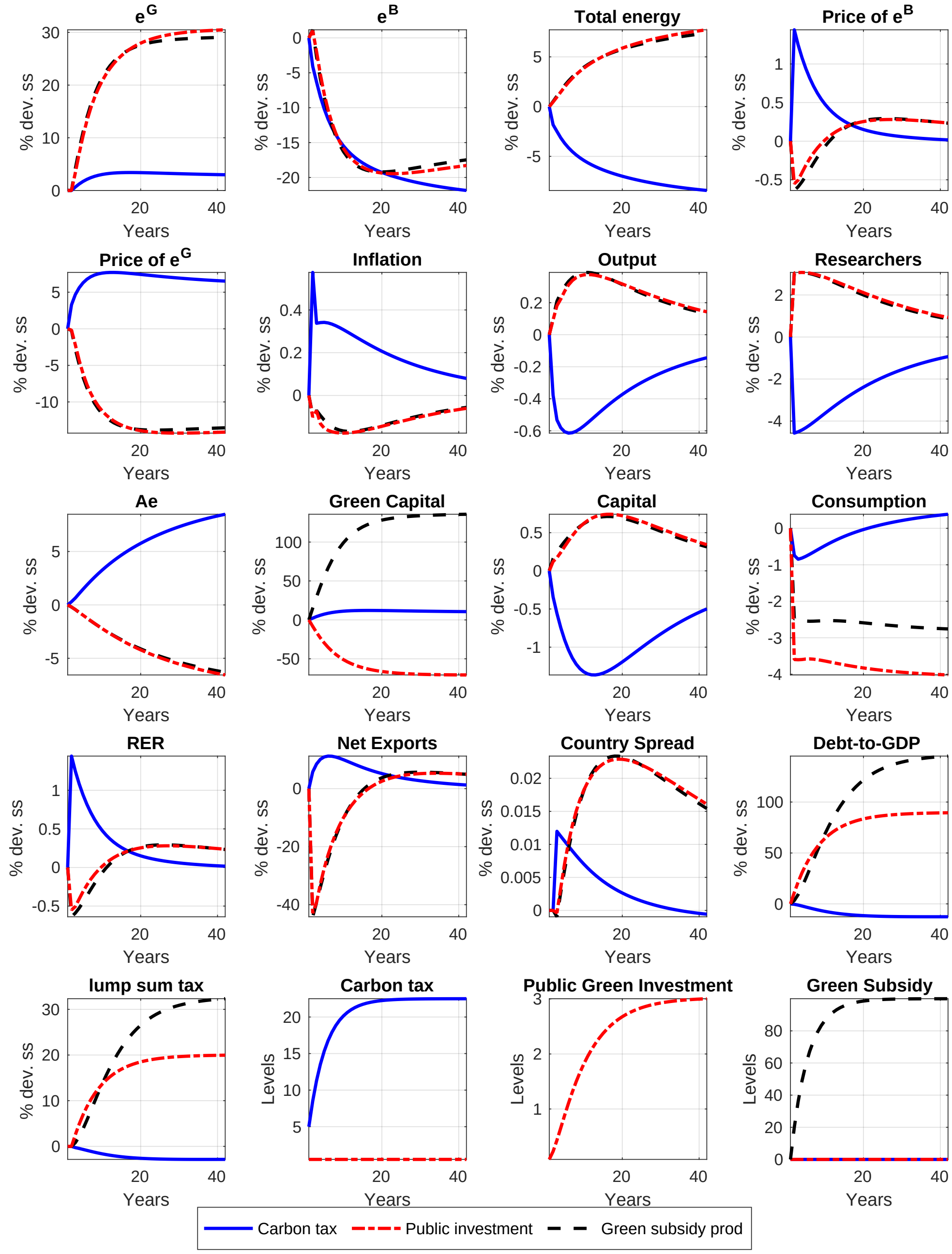
Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units. Variables are in percentage deviations from the initial steady state except for the carbon tax, which is in levels.

Figure A.3: Transitional dynamics: The role of monetary policy



Note: Dynamics for the first 40 years of transition from initial to a new steady state where carbon taxes increase from 5 to 60 final consumption units for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; black discontinuous lines are the case of $\phi_\pi = 3$; and red dashed lines are the case of $\phi_\pi = 1.1$. Variables are in percentage deviations from the initial steady state except for the carbon tax.

Figure A.4: Transition using different fiscal instruments

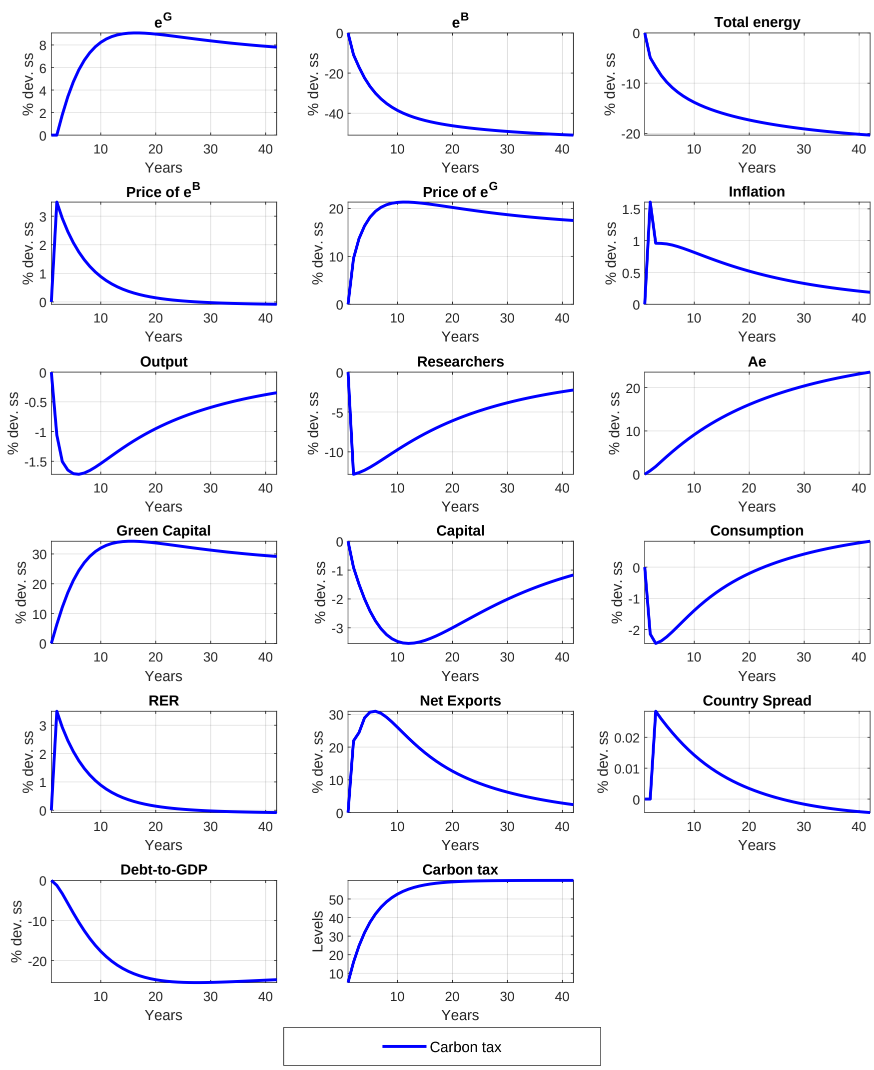


Note: Dynamics for the first 40 years of transition where carbon taxes increase from 5 to 22.5 final consumption units (blue continuous lines); subsidies change from 0 to 100% (black discontinuous lines); and public investment changes from 0 to 3% of GDP (red dashed lines). Carbon taxes, green subsidies, and public green investment are in levels. The rest of the variables are in percentage deviations from the initial steady state.

A.7 Transitional dynamics for the whole transition period

We simulate a transition of 200 periods and, in the text, show transitional dynamics for the first 40 years. All policies are fully implemented within the 40 periods, but some variables continue to adjust until they finally converge at T=200. Figure A.5 shows the full transition.

Figure A.5: Transitional dynamics: 200 years

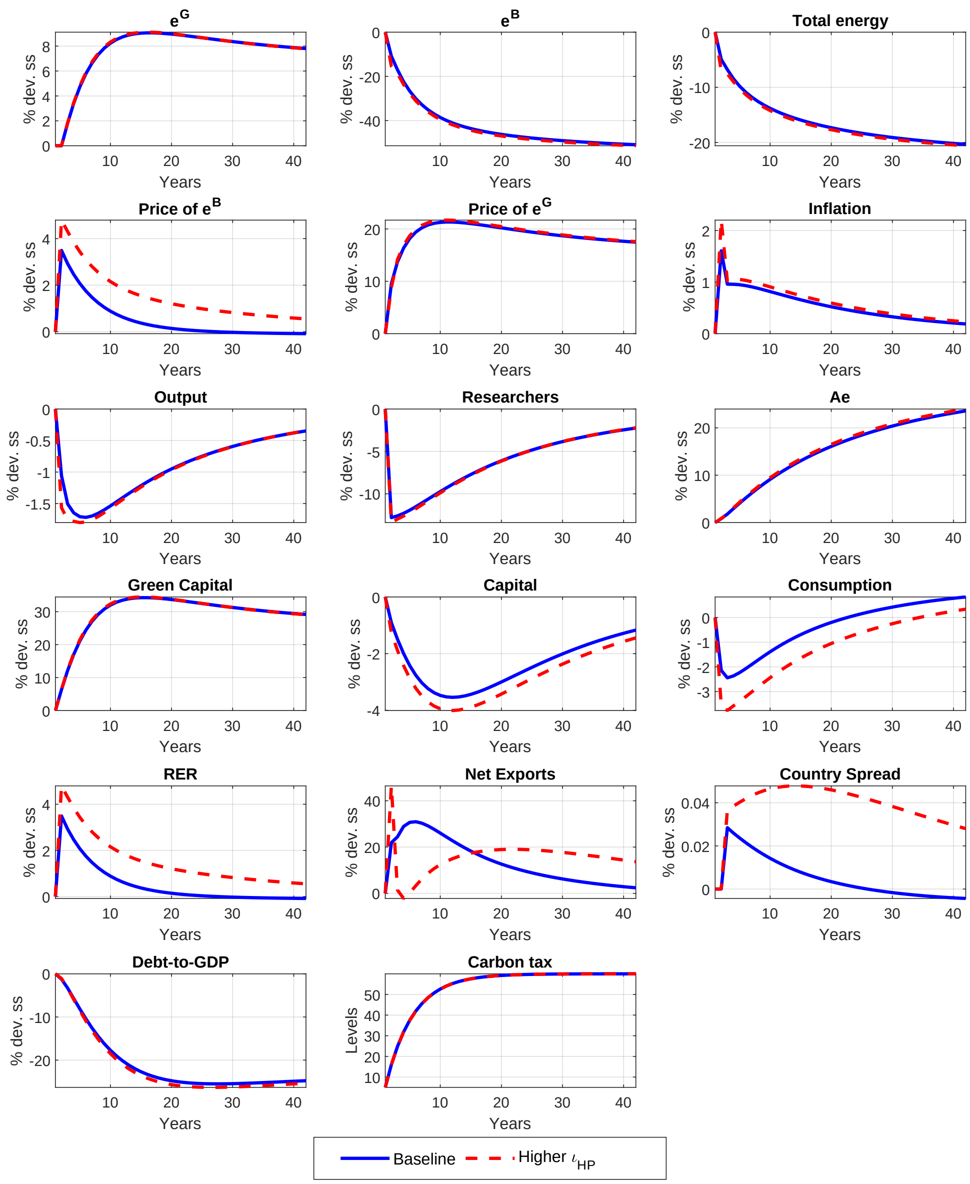


Note: Dynamics for the entire transition period where carbon taxes increase from 5 to 60 final consumption units. Variables are in percentage deviations from the initial steady state, except for carbon taxes, which are in levels.

A.8 The role of price rigidity

In Figure A.6 we show the role of price rigidity.

Figure A.6: Transitional dynamics: The role of price rigidity

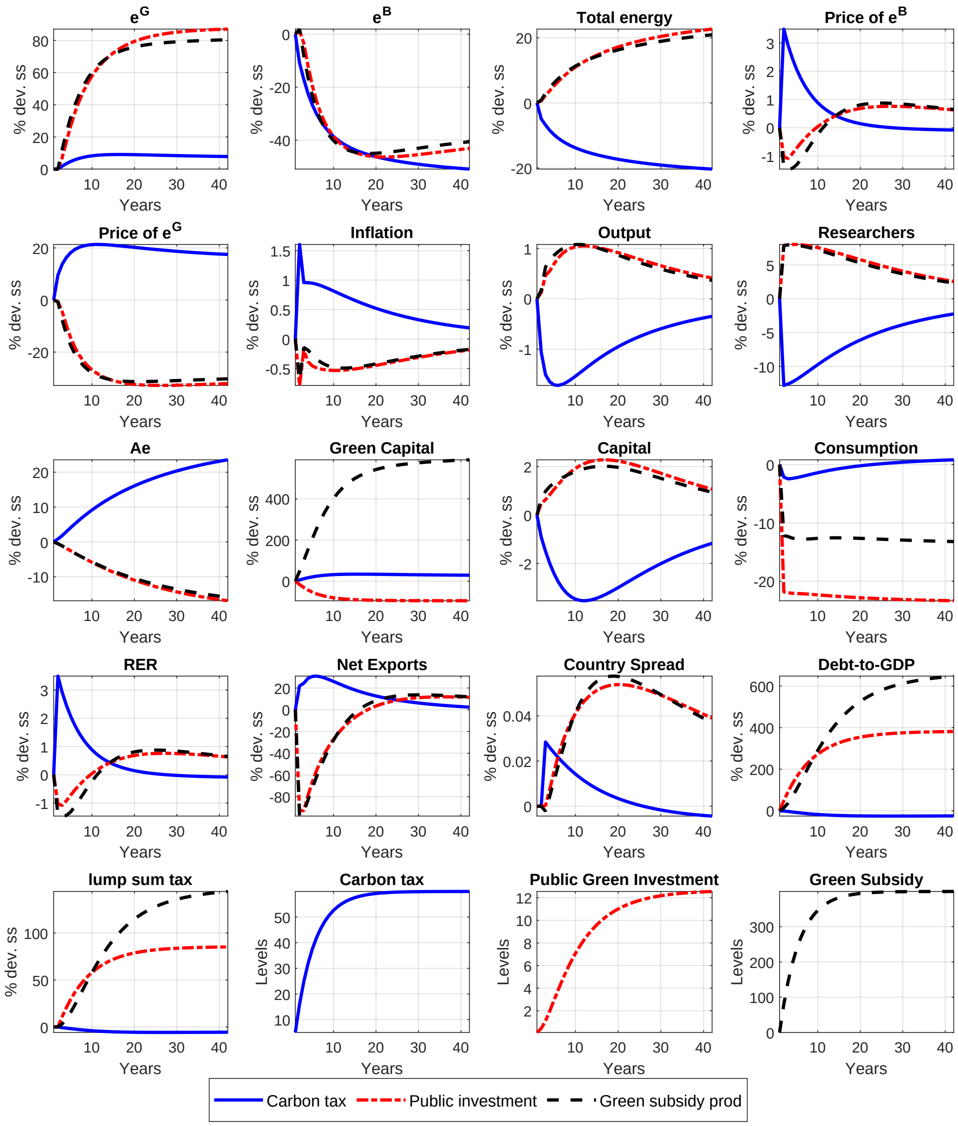


Note: Dynamics for the first 40 years of transition from the initial to the new steady state where carbon taxes increase from 5 to 60 final good consumption units for different parameters of the monetary policy rule. Blue lines represent the baseline calibration; red dashed lines are the case of $\iota_{HP} = 120$. Variables are in percentage deviations from the initial steady state, except for the carbon tax, which is in levels.

A.9 The transition with subsidies and public green investment

Figure A.7 illustrates the adjustments required in green production subsidies and public green investment to achieve a green transition comparable to that induced by increasing brown taxes from 5 to 60 units.

Figure A.7: Transition with subsidies and green investment

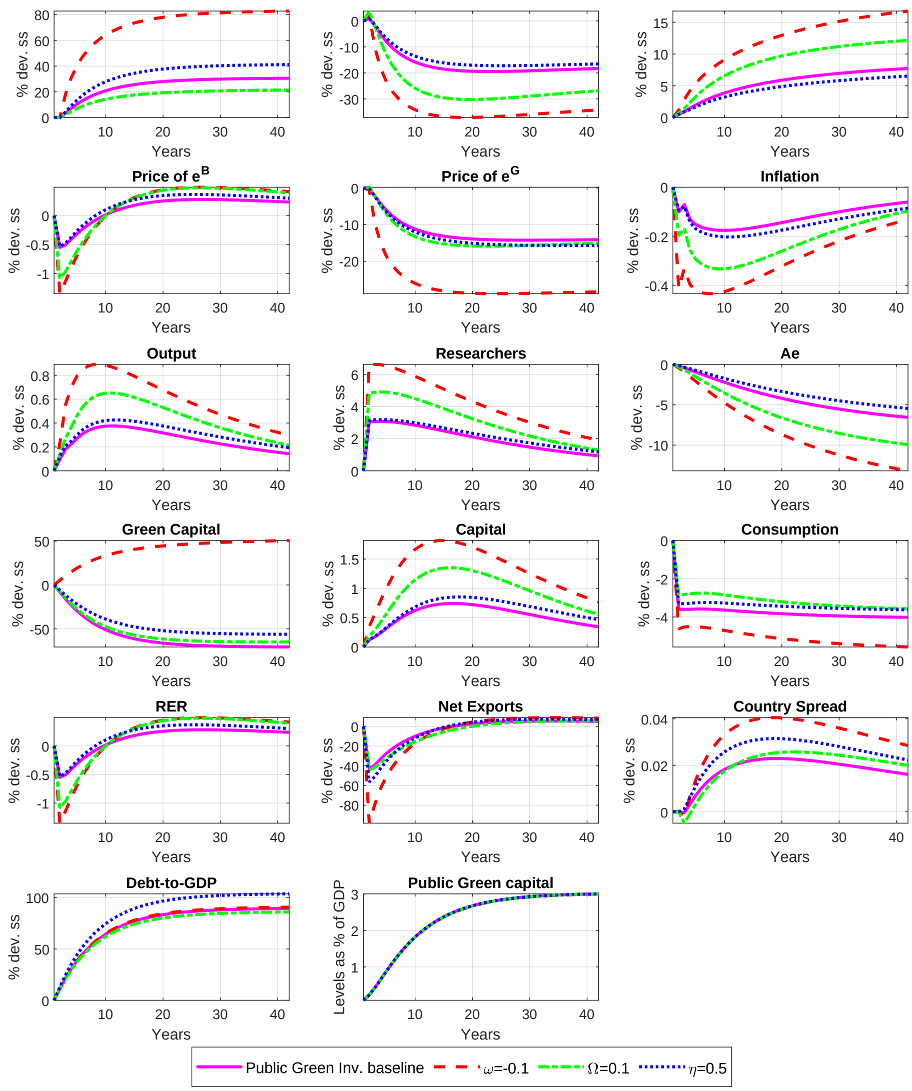


Note: Dynamics for the first 40 years of transition from the initial to a new steady state where carbon taxes increase from 5 to 60 final good consumption units (blue continuous lines); where only subsidies increase from 0 to 400% (black dashed lines); where only green public investment increase from 0 to 12.5% of GDP (red dashed lines).

A.10 The role of energy production parameterization

Figure A.8 shows the role of different parameters in energy production for the effectiveness of public green investment.

Figure A.8: Sensitivity of energy production



Note: Dynamics for the first 40 years of transition from the initial to a new steady state where green public investment increases from 0 to 3% of GDP. Purple continuous lines show the transition with the baseline calibration, and red dashed lines show the transition when $\omega = -0.1$; Green dashed lines the case of $\Omega = -0.1$ and blue dotted lines the case of $\eta = 0.5$. Variables are in percentage deviations from the corresponding initial steady state, except for green public investment, which is in levels as a percentage of GDP.